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THE GEOLOGY AND ORE DEPOSITS OF CHAMBISHI, NORTHERN RHODESIA.

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CONTENTS.

INTRODUCTION 131
GEOLOGY:
Rock Formations 135
Structure 137
Metamorphism 140
Weathering 141
THE ORE:
Oxidized Zone 142
Primary Mineralization 144
Paragenesis 149
Zoning 150
ORIGIN OF ORE 151

INTRODUCTION.

THE Chambishi copper deposit is located in the N'Kana Concession, Northern Rhodesia, and as seen on the Concession map, is centrally situated in the copper belt. It is still in the development stage, but drilling to date has indicated 25 million tons of sulphide ore, averaging 3.7 per cent. copper.

The bedded character and simple structure of most of the deposits of the district have occasioned their rapid and accurate development by drilling along the strike at intervals of about 1000 feet, but at Chambishi complicated folding necessitated additional work to expose the structure before tonnage estimates and plans for mining methods could be made.

A fact of great importance, and one which resulted in bringing out the most interesting features of the problem, was that it proved possible to get the necessary information from shallow pits. The essential structural features were obtained by means of some 350 of these pits and short cross-cuts, the pits having an average depth of 35 feet. The examination of the area was made and completed during the last four months of 1929.

Unfortunately, of the 20 drillholes at Chambishi, 13 were sunk by churn rigs and few dips were made available from these holes. Also the rapid changes in sedimentation and the lens-like character of some beds made correlation from sludges difficult. The churn drill, therefore, added little towards solving the structure, rather in some cases, the sludges were a cause of confusion.

The structure of Chambishi was solved from pits by projecting dips of beds, pitches and axial planes of folds to greater depths, and where possible interpolating from pits to boreholes.

Three features of the sediments were of great aid in this work. First, certain strata have unique physical characteristics that render them useful as key beds. Secondly, many of the sandy layers are cross-bedded and ripple-marked, so that over-turning is in most cases easily detected. Finally, the metamorphosed argillaceous members show schistosity and fracture cleavage in addition to bedding, so that the attitude of the axial planes and pitches of folds can be observed in many pits.

It is to be noted that since the completion of this work, subsequent drilling in several places has checked the accuracy of the geologic sections drawn from pit data.

It is with pleasure that I express my gratitude to those who in many ways aided me. The late T. F. Andrews, G. A. Wallis and L. C. Armstrong made accurate and valuable preliminary investigations at Chambishi in 1927–8, and I. W. Moody did fine work, especially in correlating the churn drill sludges. His detailed knowledge of the formations was of

great value, and his original geologic column has been changed but slightly in spite of much subsequent pitting and drilling.

I am especially grateful to W. F. Garlick for many ideas on the structure, and for his help in preparing some of the sections. I wish also to express my thanks to Dr. Anton Gray and Professor Alan Bateman for their kindness in correcting this paper.

Thanks are also due to the Rhodesian Selection Trust Limited for permission to publish this article.

GENERAL GEOLOGY.

It is not intended to give in this paper a detailed description of the geology of the region, as this has been well covered by the writers listed in the Bibliography. A short summary of the geology and a glance at the geologic plan of the N'Kana Concession will provide the reader with sufficient background for an understanding of this paper.

The area containing the copper belt is part of an elevated peneplain lying about 4000 feet above sea level and having a maximum relief of less than 1000 feet.

Rejuvenation is now taking place and the country is in a state of extreme youth. A few monadnocks of basement schist and lower Roan quartzite relieve the country of a gently rolling topography.

The climate is sub-tropical, there being two seasons, wet and dry. The wet season is from November to April, and the average rainfall is 50 inches. The temperature ranges from freezing to 96° F. in the shade. The average temperature for 1928–9 was 70° F.

The oldest rocks of the region are those of the Lufubu and Muva systems, and consist of highly metamorphosed sediments that were intruded by granite before erosion wore them down to form the floor on which the System of the Katanga rests.

The System of the Katanga is made up of a thick series of probably continental sediments which is readily divided into (1) the Série des Mines, containing all the known bedded

copper deposits, and (2) the conformably overlying Kundelungu series.

The Série des Mines is divided by Gray [1] into three groups, the lower and upper Roan and the M'Washia. The lower Roan is dominantly feldspathic sandstones, shales and some dolomite, and contains all the known disseminated copper sulphide ores of the region. The upper Roan is predominantly dolomitic, and most of the oxidized ores of the Congo occur in this horizon. The M'Washia includes sandstones, oölite beds, banded and carbonaceous shale. The average thickness of the Série des Mines is probably over 5000 feet.

The overlying Kundelungu has a fluvio-glacial conglomerate at the base, which grades into beds of shale, limestone and arkoses, having a total thickness of 12,000 feet.

A younger granite intrudes the lower Roan and is probably younger than the Kundelungu; gabbro and diabase are also intrusive into these sediments.

The Chambishi ore deposit lies near the base of the lower Roan group of the Série des Mines.

Rock Formations.

The descriptions given below apply to the unweathered rocks obtained from drill cores at Chambishi, as their true nature in many cases can only be guessed at from specimens obtained at or near the surface.

The rocks are thoroughly weathered to depths exceeding 50 feet and, depending on their attitude and nature, may be altered down to 300 or 400 feet. Near the surface hard quartzites may appear as friable sands, schist and shale as clay, and dolomites as masses of talc and chert.

Footwall Rocks.—Rocks of the Lufubu and Muva systems are missing at Chambishi, and here the oldest sediment is the footwall quartzite and conglomerate at the base of the Série des Mines. The thickness of this bed is not known because its lower part has been removed by intrusive granite. Its

[1] Gray, Anton, "The Correlation of the Ore-Bearing Sediments of the Katanga and Rhodesian Copper Belt," ECON. GEOL., vol. 25, pp. 783–804, 1930.

greatest known width is not much more than 100 feet. It consists chiefly of feldspathic, micaceous quartzite, containing thin lenses of grit and conglomerate. One fairly persistent conglomerate occurs just below the ore shales. In No. 2 Incline shaft, and in several cores, there occur in the footwall quartzite vertical quartz veins about 1 to 2 cm. in width. These veins stop at the base of the ore shale.

In one or two instances a little chalcopyrite and bornite have been noted as coatings on minute fractures in this rock.

Ore Shale.—The ore shale, averaging 75 feet in width, is a fine-grained, dark green, sandy calcareous argillite. The upper part of this bed is more sandy than the lower part, is much less schistose, and differs little from sandy shales which occur further in the hanging wall. The upper sandy part grades downward into the ore host, which contains more calcium and magnesium carbonate, and within 5 to 20 feet of the footwall the rock becomes a dolomitic schist. Whereas the top part of the ore horizon is well and finely bedded and has pronounced fracture cleavage, the bottom part is intensely crumpled, schistose and filled with quartz-calcite vein material. Thus, the ore shale may be divided into three zones that grade into each other, first, the upper or hanging wall zone from 20–50 feet thick, which is dominantly sandy and fine-grained and which carries only a little pyrite and chalcopyrite finely disseminated near the base. Below this the rock contains over ten times as much carbonate and is more schistose, but still shows bedding. This rock may prevail for 20 or 30 feet and contains practically nothing but finely disseminated bornite and a few veinlets of chalcopyrite and bornite paralleling bedding or schistosity. The lower part of the ore shale is a contorted schist and the mineralization is composed of coarse massive bornite and chalcopyrite with much introduced quartz and calcite.

In some places this zone is separated from the footwall quartzite by a 2 to 5 feet quartz vein that carries bornite, chalcopyrite, and a little chalcocite.

Hanging-Wall Rocks.—Above the ore shale lies about 100 feet of interbedded quartzite and quartz-mica schist. The quartzites lens considerably, but there are three, about 20 feet thick, that persist along the strike for several thousand feet. The hanging wall quartzite is one of these that lies just above the ore shale.

The upper quartzite, averaging 50 feet in width, is next in succession. It is a coarse, white, feldspathic, calcareous rock that contains remarkably fine cross-bedding. Because of its width and texture it is an excellent marker, and much of the interpretation of the structure was obtained by tracing this bed.

Resting on the upper quartzite are interbedded schists and quartzites which, like all the sediments at Chambishi, are calcareous. Because of the extremely sharp changes in composition and texture, these beds represent rapid and violent changes in the original sedimentation. The quartzites average two to four feet in thickness, and are intricately cross-bedded and ripple-marked. The attitude of these structures indicates that the sediments came from the north. The upper part of this horizon is dominantly calcareous quartz-mica schist. The thickness averages about 75 feet.

A white to pink dolomite, about 40 to 50 feet thick, lies on the schist and quartzite zone. It is medium grained, massive, and contains a considerable amount of silica and talc. The thickness and appearance of this bed make it a good marker in the drill holes, and on the surface it is an even better key bed, as it weathers into a distinctive talc schist containing large chert boulders.

For about 250 feet or so above the dolomite, a greenish, sandy talc schist prevails. It contains small lenses of coarse feldspathic sandstone that are mostly under 6 inches in thickness. This bed grades upward into the dolomite of the upper Roan.

Gabbro and diabase cut this dolomite anywhere from 100 to 400 feet above its base. The gabbro is a dark, medium to coarse-grained rock that carries sparing amounts of pyrite,

pyrrhotite and chalcopyrite. At Chambishi it appears to be a sill or flat dike over 1000 feet thick.

Above the gabbro is more dolomite, which lies below the banded shales of the M'Washia group.

Granite.—The granite at Chambishi is a medium-grained, gray rock, containing quartz, acid feldspar and biotite. It unquestionably intrudes the Roan sediments. At the base of the ore shale it appears to have been injected along a fault and is now an intrusion breccia containing fragments of both the ore shale and footwall quartzite. This breccia, as well as the main mass of granite, contains a little copper.

Structure

The geologic plan of the Concession (Fig. 1) shows that Chambishi lies on the north side of a large basin. The local structure consists of a series of south-dipping recumbent east-west folds that are superimposed on a large bench. The axial plane of this bench probably strikes northwest and dips steeply to the northeast; it appears to have some gentle drag folds on its flat northeast limb.

The east-west folds are arranged *en échelon* and pitch west from 0 to 32° except locally, where, cutting across the crests of small northwesterly folds, they pitch a few degrees to the east.

The maximum intensity of the east-west folds is reached near the main crest of the bench which is probably near drill hole 34. Here the beds which, when flat, extended for about 2000 feet, are now squeezed into a horizontal distance of 1200 feet, or a 5 : 3 ratio. East of this crest on the flat side of the bench the folds die out slowly, but to the west, on the steep limb, they die out very quickly.

The fracture cleavage and schistosity generally parallel the axial planes of the east-west folds, which dip about 70° south.

Many small faults occur, both normal and reverse, but only a few are large enough to be of interest from a mining standpoint. There are two thrust faults near drillhole No. 5, both having a net displacement of not over 100 feet. These faults

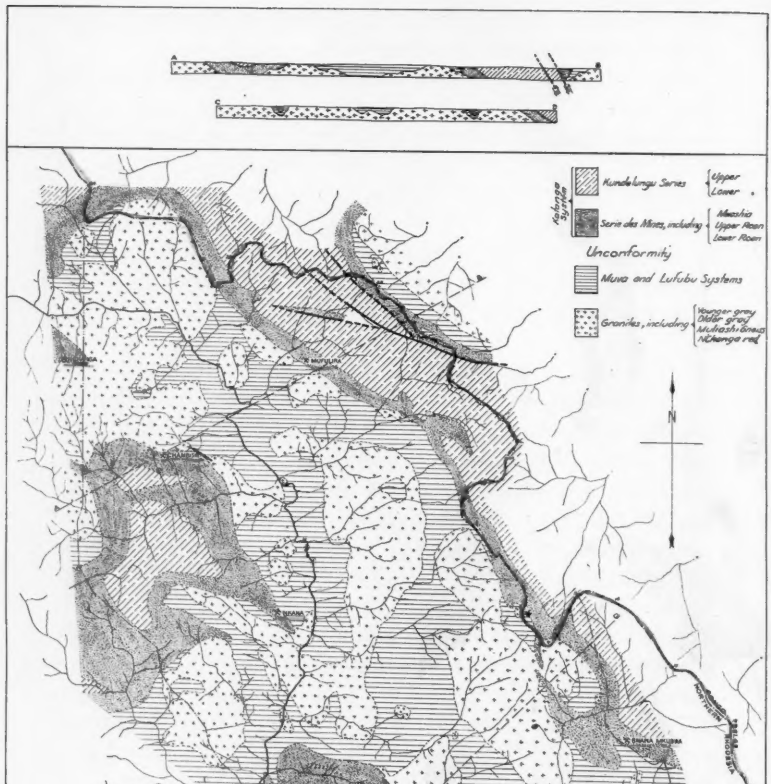

FIG. 1. Geological Map of the N'Kana Concession, Northern Rhodesia.

die out along the strike and along the line of drill holes from 1 to 33 the pressure seems to have been relieved by several small folds. A similar thrust extends from near drill hole No. 6, eastwards for over 1500 feet.

The incompetent ore shale and schist have slid on the tops of the competent beds. This has resulted in drag folding, and faulting of a very intricate nature. This sliding has caused the softer beds to thin in the limbs and thicken in the crests of folds.

The distribution and unaltered condition of the gabbro suggest that it was intruded as a sill or flat dike after the folding took place. In a general way it follows the folds, but locally it cuts across the bedding. Mostly it seems to have been injected more or less parallel to the bedding of the dolomite of the upper Roan, since several drill holes have passed through the gabbro into the underlying dolomite. At Chambishi, it occurs at least 700 feet stratigraphically above the base of the lower Roan.

Garlick [2] has suggested a sill-like method of intrusion for the granite, for excepting minute structures, in nearly every observed case the intrusive contact varies but a few degrees from the dip of the sediments, and the trace of the granite-sediment contact on the surface is remarkably even.

Between the ore shale and the footwall quartzite there is an intrusion breccia of medium-grained granite containing fragments of ore shale, quartzite, schist, quartz and granite. Toward the eastern end of Chambishi there are two of these sills, one at the footwall of the ore shale and one paralleling the crest of a fold. These intrusions have evidently followed planes of weakness, in one case what amounts to a bedding plane fault, and in the other case the shattered crest of an anticline. This indicates that in its course the magma moved not vertically but diagonally along the base of the Roan, choosing the paths of least resistance. From this it follows that the granite came in after folding took place.

The two types of folding at Chambishi appear to have

[2] Garlick, W. F., Personal communication.

formed almost simultaneously, and are probably the result of stresses which formed the large northwesterly-striking anticline of the N'Kana Concession.

Metamorphism.

Dynamic metamorphism has caused the major changes in the sediments since their original deposition.

The sandstones were changed to quartzites, shales to slate and schist, and the limestones and dolomite are now recrystallized in many cases to coarse marble.

The quartzites and marbles are well jointed and fractured and the argillaceous rocks show either well developed fracture cleavage or schistosity.

Near the crests of large folds, drag folds are abundant in the incompetent beds. Especially in the base of the ore shale there is evidence of intense movement. Here the rock is a complex of contorted schist filled with a cement of pegmatitic material.

The sediments as a whole show the result of intense metamorphism in a zone of combined flow and fracture. The soft members show characterictics that are the result of flow, such as schistosity and drag folding. The more competent beds, however, such as the upper quartzite, show features resulting from both flow and fracture. In places this stratum is faulted and intensely fractured, and the fractures are commonly found to contain quartz veins that have altered the rock near the contact. These quartz veins are indeed a feature of this particular horizon and are confined to its limits, being most numerous near crests of folds. Nevertheless, the quartzites, taken as a whole, had not sufficient strength to control the folding, for the type folds at Chambishi are similar rather than concentric, and even the competent upper quartzite shows some thickening on the crests of anticlines.

The results of mineralizers and hydrothermal activity are much in evidence at Chambishi. It seems probable that the dolomitic beds have been silicified and made talcose by granitic emanations. In one place, where the ore shale was probably

a dolomite, and where it was cut by granite, there is almost complete replacement of the original rock by silica and talc. In all known cases the ore shales near the base are permeated with vein material, and in thin section may be seen secondary growths of quartz and feldspar and introduced sericite and tourmaline.

The dolomites above the ore shale are also talcose and more or less silicified, and small pegmatites are commonly found along fractured zones and fault planes. Large quartz veins, flanked by altered country rock for a foot or more from the contact, are numerous, especially in the upper quartzite.

Some of the dolomite of the upper Roan near the gabbro shows intense recrystallization, and the development of contact-metamorphic minerals, such as actinolite and zoisite. The altered rock is in most instances dark green and is spotted with metacrysts in such a way as to resemble a porphyry.

The substances introduced from the magma include water, silica, potash, calcium, magnesia, boron, sulphur, copper, iron, zinc, and cobalt.

Weathering.

Except in a few isolated cases in or near streams, outcrops are lacking in the region around Chambishi. Decomposition is far in advance of transportation, and in observed cases the bed rock is covered by a mantle of over 15 feet of soil that grades downward through as much as 20 feet of subsoil into a thoroughly weathered formation.

Dolomites and gabbro may be covered by over 100 feet of clayey soil, whereas hard shale, schist, quartzite and granite are overlain by an average soil mantle of about 20 feet.

The soil weathered from shale and quartzite is dominantly red or reddish; that weathered from silicious schist is yellow to brown; granite yields a light yellow to gray soil, and calcareous rocks and gabbro weather to deep red.

Laterite, as noted in many other districts, is found over gabbro, but may occur over any rock, and in most places is probably the result of intense decomposition in place.

In areas underlain by quartz veins it is common to find a horizontal zone of coarse quartz rubble between the soil and subsoil. In several cases it has been possible to trace this rubble from the original quartz vein to where, because of disintegration and solution, it consists of only scattered rounded pebbles, having a washed or polished appearance.

THE ORE.

All the ore is confined to the lower 50 feet of one horizon, the ore shale. The shape of the ore body is therefore approximately that of this stratum, and thins on the limbs and thickens on the crests of folds.

The proved strike-length is a little over 4000 feet, the average thickness about 25 feet, and although the extent down the dip is unknown, the deepest holes yielded rich ore at a vertical depth of 1200 feet.

From data at present available the lode appears to widen with depth towards the east. Thus it seems that the pitch of the ore shoot coincides roughly with that of the main bench.

The Oxidized Zone.—The ore shale at Chambishi outcrops intermittently for about 500 feet along the strike. Like most of the lode outcrops of the region it is rather unimposing in appearance. It consists of a silicified sandy shale with disseminated malachite and contains from 2 per cent. to 3 per cent. copper.

At or near the surface, the ore carrier has been leached, so that the assays average 1 per cent. lower than the primary ore. However, the highest assay over a 2-foot width near the surface is 5 per cent., although the high-grade primary ore in places runs from 12 per cent. to 25 per cent.

Copper within 100 feet of the surface is chiefly in the form of malachite, which is so finely disseminated that in some specimens that contain 3 per cent. copper it cannot be seen by the naked eye.

A black oxide of copper, cobalt, manganese and iron occurs in the ore shale, and also in the surrounding rocks at shallow

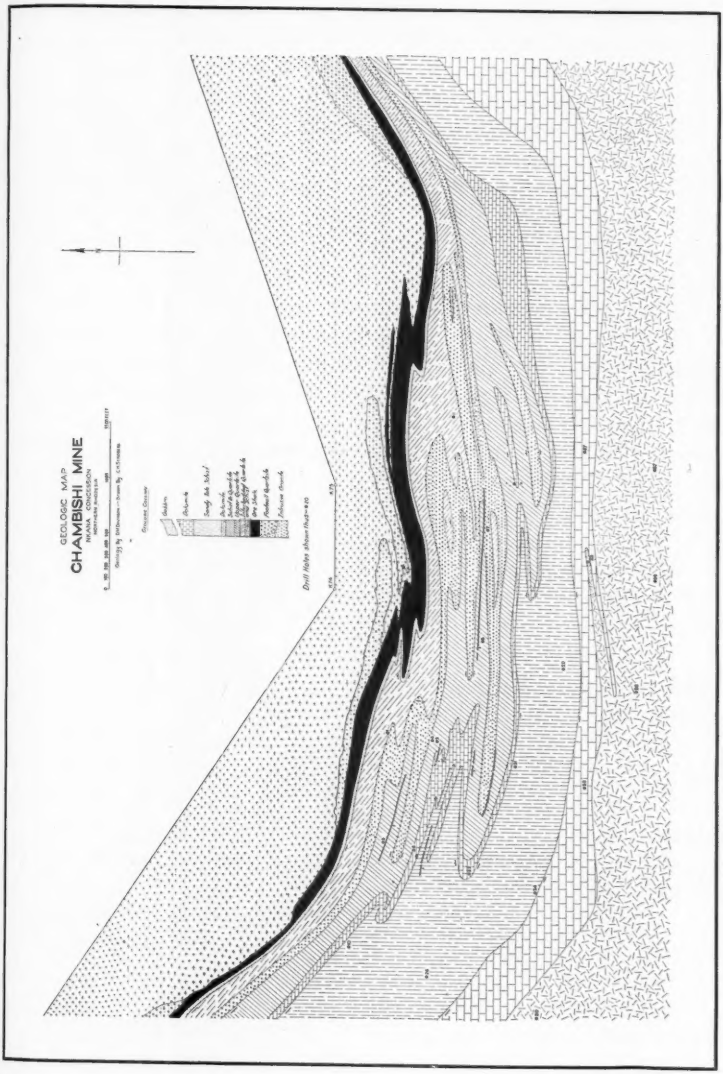

FIG. 2. Geologic Map of Chambishi Mine, N'Kana Concession. Geology by D. M. Davidson. Drawn by C. H. Stroberg.

depths. As these inclosing rocks, such as the hanging wall and footwall quartzite, do not carry even a trace of copper at depth it is assumed that much of this black oxide is transported by lateral migration of solutions.

The average depth of the water table is from 40 to 50 feet, with a fluctuation of 5 feet between wet and dry seasons. Oxidation, however, extends to greater depths, and undoubtedly supergene action predominates to 300 feet. Between 300 and 400 feet sulphides predominate and below 400 feet there is very little oxide.

There is not much limonite boxwork to indicate the presence of the former sulphides in the weathered ore shale except where it has been silicified. The formation of malachite, extensive leaching for vast periods of time, and slumping have here destroyed most of the criteria by means of which the presence of former sulphide minerals may be predicted. In the harder shale, however, there is a fair amount of limonite which is brown, confined to cavities, has angular patterns and is finely disseminated throughout the rock in the same manner in which sulphides occur at depth. A thorough study of the leached portion of the ore shale at Chambishi leads to the following conclusions:

1. Where the rock is hard and outcrops, there exists brown "boxwork" limonite which definitely indicates former sulphides.

2. It has not been found possible to make quantitative estimates of the former copper content from the amount of this limonite.

3. The average grade within 50 feet of the surface is at least 1 per cent. lower than the corresponding sulphide average.

4. Where there are many cubes and pyritohedra of limonite after pyrite in a surface specimen which has a lean copper content, better values are not to be expected with depth.

Primary Mineralization.—The ore at Chambishi is epigenetic and is to be classified probably with deposits of the deep vein zone. It appears to be related to the folding, and

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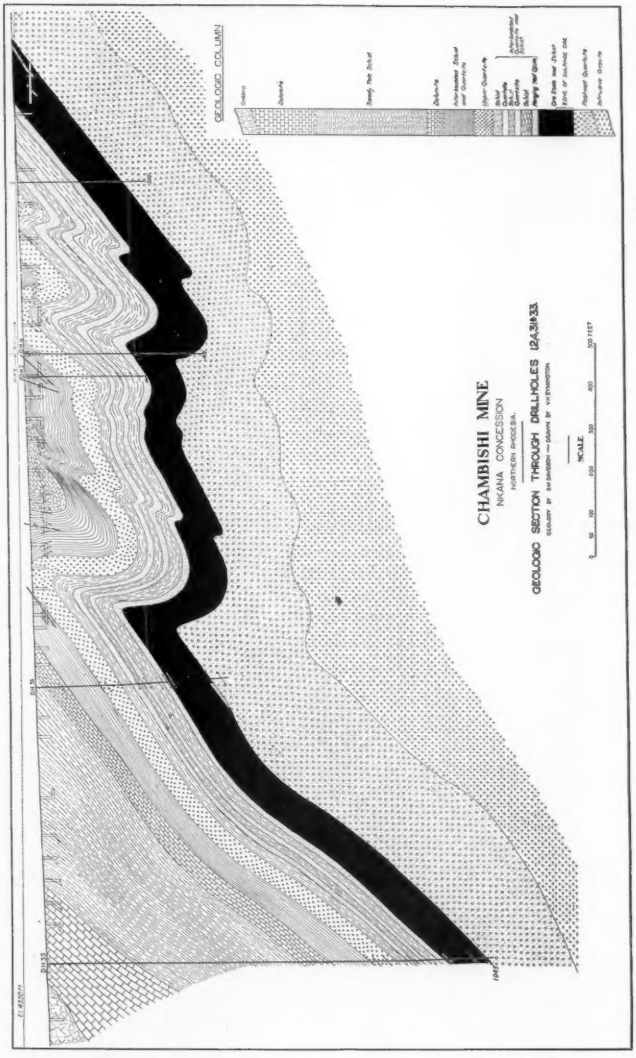

FIG. 3. Geologic Section through drill holes 1, 2, 4, 31, and 33, Chambishi Mine.

FIG. 4. Geologic Section through drill holes 7, 23, and 35, Chambishi Mine.

the highest grade and greatest widths of ore are found near or on the crests of folds, as in drill holes 4, 6, 22, 34, 31, and 35, whereas drill hole 31, which is located well down from the crest of a fold, is a low-grade hole. The core shows sulphides concentrated in crests of tiny drag folds, and in veinlets parallel to openings, such as schistosity, fracture, and cleavage.

As with all the deposits in the district, the ores are distinctly bedded. The individual grains are finely dissemi-

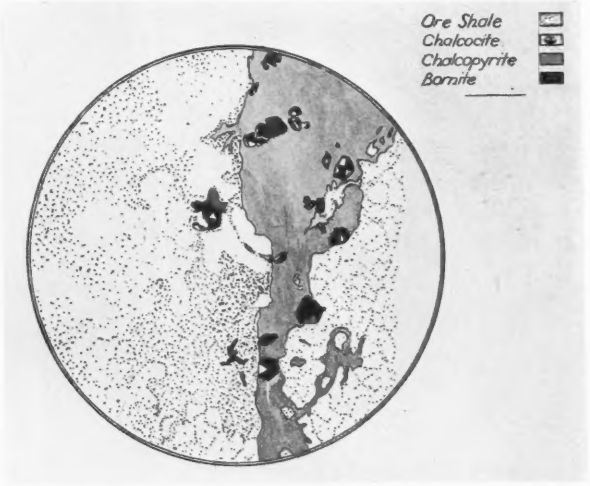

FIG. 5. Chalcocite crystals in a veinlet of chalcopyrite and bornite in Chambishi ore shale, from D. H. 35. Depth, 1198 ft. × 6. Drawn by V. H. Symington.

nated, but there are fine grains in the fine-grained beds, and coarser grains in the coarser beds. Much of the sulphide is in tabular or oval grains, whose long axes parallel bedding, but if the rock is schistose they may be oriented along the bedding, but with their long axes paralleling schistosity.

The majority of the ore occurs as fine disseminations. The grains average about 1 mm. in size but range from .02 to 5

cm. in diameter. Numerous small quartz-calcite-biotite veinlets that contain chalcopyrite, bornite, and in some cases chalcocite, penetrate the host rock along bedding or fracture planes.

Proximity to the intrusive granite seems to have a direct bearing on sulphide deposition. The two projections of granite that are in evidence near drill holes 10 and 11 are undoubtedly the partial cause of lack of ore in these holes; for

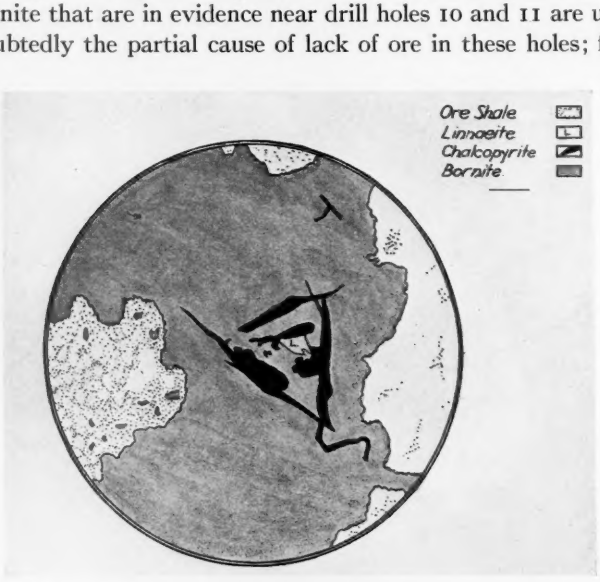

FIG. 6. Chalcopyrite cutting bornite in triangular pattern. Chambishi, D. H. 35. Depth, 1205 ft. × 6. Drawn by V. H. Symington.

although the poor mineralization in drill hole 10 may be partly accounted for by the lack of intense folding there, drill hole 11 was barren in spite of the fact that it went down in the crest of a fold. It is significant that where the granite cuts well into the ore shale there is no ore, as in the case of drill holes 26 and 11, or the ore is farther in the hanging wall, as in drill hole 8.

Paragenesis.—The predominant sulphide in the ore[3] is bornite, and hypogene versus supergene bornite is therefore a vital question in the life of the mine. Bornite and chalcopyrite make up fully 98 per cent. of the primary copper minerals so far exposed, and a little pyrite, glance, and covellite are in evidence.

All the chalcopyrite in the Chambishi deposit is undoubtedly of hypogene origin, and granting this, bornite must also be hypogene, as brought out by the following observations:

POSITIVE EVIDENCE.

1. Relicts of bornite surrounded by rims of chalcopyrite.
2. Bornite cut by chalcopyrite veinlets.
3. Graphic intergrowths of triangular laths of chalcopyrite in bornite.
4. Laths of chalcopyrite disappear on heating, which is taken by many investigators as evidence of solid solution formed at high temperature.
5. Triangular and parallel lath-like intergrowths of bornite, chalcopyrite, and linnæite strongly suggest contemporaneous deposition of these minerals.
6. Bornite and chalcopyrite have sharp, well-defined contacts called "mutual" by some workers to indicate hypogene contemporaneous deposition.

NEGATIVE EVIDENCE.

1. The percentage of bornite in the ore is as great at 1200 as at 400 feet.
2. The bornite does not increase along porous channel-ways, such as at the footwall, or along troughs of synclines.
3. Where there is obviously supergene action with leaching and malachite, chalcocite replaces bornite and chalcopyrite in a network pattern, which is never seen in bornite-chalcopyrite relationships.
4. Relatively small amounts of pyrite indicate a paucity of iron in the mineralizing solutions; therefore, bornite is to be expected.
5. If bornite were supergene one would expect it more along veinlets and in the coarser sandy beds, where supergene solutions would first attack. However, the fact is that in most cases the very fine mineralization is entirely disseminated bornite, whereas chalcopyrite occurs with bornite in coarser layers and in veinlets.
6. If much supergene action had taken place one would certainly expect more chalcocite than the amounts now in evidence.

[3] The term "ore" is used here for rock which assays over 2.5 per cent. copper.

7. All the evidence examined by the writer in the N'Kana Concession indicates that in supergene replacement chalcopyrite goes directly to chalcocite and not bornite. For instance, on the Chambishi western extension, where obviously in shallow holes there has been oxidation, chalcocite replaces chalcopyrite directly.

What chalcocite exists is probably mostly of supergene origin, but some crystals of glance surrounded by chalcopyrite, as shown in Fig. 5, would seem to indicate that some is hypogene.

The only other sulphides so far determined at Chambishi are sphalerite and linnæite, both of which occur intergrown with chalcopyrite and bornite. Figure 6 shows chalcopyrite, linnæite, and bornite intergrowths.

The order of paragenesis of the hypogene minerals at Chambishi is as follows: Pyrite, then more or less contemporaneous linnæite, bornite, chalcopyrite, sphalerite, and chalcocite.

Pyrite in all known cases is the earliest sulphide. It occurs mostly as striated cubes, and some pyritohedrons, and in many specimens is surrounded by chalcopyrite.

Most of the linnæite appears to be earlier than the bornite, but some of it is intergrown in a pattern that indicates simultaneous deposition with bornite and chalcopyrite. About half of the observed bornite is earlier and half later than the chalcopyrite. There is very little sphalerite at Chambishi. It occurs as sparsely disseminated fine black specks or associated with bornite and chalcopyrite in quartz veinlets in such fashion as to suggest simultaneous deposition.

What little hypogene chalcocite is in evidence appears to be almost the same age as the bornite.

Zoning.—Zoning of the sulphides is one of the outstanding and interesting features of the ore body. The lode may be easily divided into three distinct parts.

At the base of the ore are 5 to 20 feet of coarse bornite and chalcopyrite in vein-filled schist. For from 20 to 30 feet above this zone there is practically nothing but finely disseminated bornite. Above this is disseminated chalcopyrite which in places dies out into sparsely divided crystals of pyrite.

These zones are quite obvious and changes between them occur generally within a few feet.

The upper chalcopyrite-pyrite area averages about 2 per cent. copper. The middle bornite zone runs from 3 per cent. to 8 per cent., and the bottom coarse material may assay as high as 22 per cent. over a 4-foot width.

ORIGIN OF ORE.

To the writer the source of the Chambishi ore is undoubtedly the magma which solidified into granite. The granite itself carries traces of copper, and pegmatites and quartz veins that come from it also carry copper sulphides. Also, the ore shoot shows a definite relationship in regard to proximity of granite.

The cause of localization of ore in one bed has vexed geologists of the region from the first. At Chambishi the relationship seems clear. Three factors are probably involved. First and most important appears to be permeability. The obvious channel-way through which the ore came is the sheared and faulted zone at the bottom of the ore horizon. Here the rock contains many open spaces that are now occupied by pegmatitic material. All the evidence confirms this and none opposes it.

The ore is along bedding, bedding-plane fractures, schistosity, and is concentrated in the openings at the crests of folds. There is a great concentration in the schist near the footwall, and along the crumpled sheared footwall are quartz veins. Saddle reefs occur in the crests of anticlines.

Secondly, much of the sulphide replaces the original calcareous cement of the ore shale. The calcareous content of the ore horizon is highest at the footwall, where in many places the rock might be called a dolomitic schist.

As previously noted, the part of the ore horizon that carries disseminated bornite, which assays about 4 per cent. copper, has over ten times as much carbonate as the barren hanging wall of the ore shale.[4]

[4] It is estimated that about one fourth of this carbonate content consists of material introduced probably at the time of mineralization.

Proximity to the source is the third vital factor in ore localization. There is no ore either very close to or very far from the granite.

The history of the Chambishi lode may be pictured somewhat as follows:

During or shortly after the latter stages of folding, granite intruded the base of the Roan, reaching high points on the crests of large anticlines at the eastern and western ends of Chambishi. From this granite came copper-cobalt-zinc fluids fairly poor in iron. These emanations migrated, probably diagonally, along the faulted and fractured zone at the base of the ore shale, which must have been a good channel-way, and perhaps some material was conducted through the vertical joints in the footwall quartzite.

On reaching cooler rock, they penetrated the lower and more pervious part of the first hospitable bed—the ore shale. This rock they impregnated by replacement and by fracture filling until they reached the more impervious and less calcareous zone in the hanging wall.

RHODESIAN SELECTION TRUST,
N'DOLA, NORTHERN RHODESIA.

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BENTONITE FROM VENTURA, CALIFORNIA.

PAUL F. KERR.

INTRODUCTION.

For some time it has been known that a soft soapy clay occurs in Miocene strata of the Ventura quadrangle, California, but the significance of the clay appears to have been overlooked. It seems, however, to warrant more particular study than has been as yet accorded it, both because of the position it occupies in the stratigraphic column and because of its bentonitic character, a feature not heretofore established. Although of stratigraphic and mineralogic interest, the clay does not appear to have any material economic value. It is true that it has been used to some extent in the purification of petroleum products. In fact, it was one of the first native clays to be so employed in California. It has also been utilized to a limited extent in the cosmetic industry. Field studies seem to show, however, that washable clay has not yet been found in sufficient quantities to justify any extensive commercial exploitation.

The Ventura quadrangle embraces an area 14½ miles east-west by 17½ miles north-south along the shore of the Santa Barbara Channel, 70 miles northwest of Los Angeles. The southwestern corner of the quadrangle overlaps the water of the Channel. The remainder includes a mountainous coastal area in the vicinity of the city of Ventura (Fig. 1). A large area of Miocene sedimentary rocks, consisting mainly of various types of shale and some sandstone, extends east-west through the central portion. Volcanic ash is present in the shale and the clay occurs in beds associated with the ash. Such beds constitute good markers in a region in which reliable horizon markers are scarce.

Exposures of the clay have been found at five localities within the Ventura quadrangle, as shown in Fig. 1. Careful search would probably uncover additional localities. It is also probable

that other occurrences not reported exist in numerous places throughout the Coast Ranges in altered pyroclastic rock. As far as known, the occurrence in the Ventura district is limited to a portion of the Modelo formation as described by Eldridge and Arnold [1] and Kew,[2] or the more strictly defined Modelo formation of Hudson and Craig.[3] The Monterey formation as described

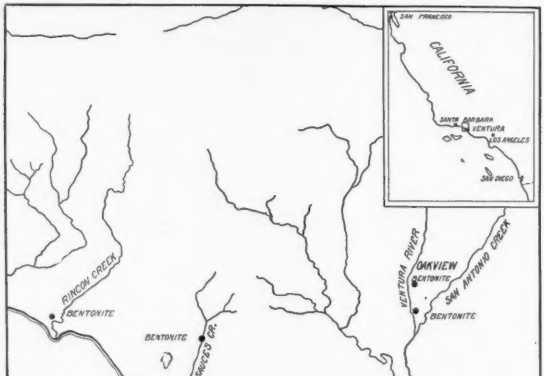

FIG. 1. Diagram showing the location of five bentonite localities within the Ventura quadrangle. The insert shows the position of the Ventura quadrangle in California.

1 Eldridge, G. H., and Arnold, Ralph, "Santa Clara Valley, Puente Hills and Los Angeles Oil Districts, Southern California," U. S. Geol. Surv. Bull. 309, 1907.

2 Kew, W. S. W., "Geology and Oil Resources of a Part of Los Angeles and Ventura Counties, Calif.," U. S. Geol. Surv. Bull. 753, 1924.

3 Hudson, F. S., and Craig, D. K., "Geologic Age of the Modelo Formation," Bull. Amer. Assoc. Petr. Geol., vol. 13, p. 509, May, 1929.

by Arnold and Anderson,[4] in the Santa Maria district to the north, in part the equivalent of the Modelo formation, probably also contains bentonite.

Samples were collected during the summer of 1929, although the occurrence had been noted on several previous occasions.[4a] The specimens were studied by optical, chemical, and x-ray methods after the author returned to the mineralogical laboratory at Columbia University. Recent studies by Ross and Kerr have shown the necessity of applying several parallel lines of investigation to the identification of the mineral constituents of clay. In view of such work it is advisable to place on record a description of bentonite involving the various methods of study as now practised with other types of clay.

ACKNOWLEDGMENTS.

The author is indebted to Dr. Clarence S. Ross of the United States Geological Survey for the opportunity to compare the Ventura bentonite with purified bentonite from previously described localities. The mineralogical study is a part of a program of research on the clay minerals being carried out in coöperation with Dr. Ross, and information obtained in the joint investigation and not yet published has been available in the present study.

Dr. W. S. W. Kew of the Standard Oil Company of California has kindly offered suggestions in the field study. In fact, Dr. Kew was the first to point out the stratigraphic importance of a description of the clay.

Professor R. J. Colony of Columbia University has assisted the microscopic study through his interest and generous conferences.

FIELD RELATIONSHIPS.

Bentonite is found in the Ventura quadrangle in beds which lie at the contact between two formational units. It occurs at the

[4] Arnold, Ralph, and Anderson, Robert, "Geology and Oil Resources of the Santa Maria Oil District," U. S. Geol. Surv. Bull. 322, 1907.

[4a] Several additional localities were discovered in the summer of 1930, after this paper had been written.

base of the Modelo formation and overlies the top of the Rincon formation.[5]

A layer of volcanic ash of variable thickness lies at the base of the Modelo formation and in places may possibly occur stratigraphically higher. The upper limit of the ash bed is marked by platy Modelo shale containing abundant foraminifera and comparatively few diatom remains. The platy shale is much harder than the ash bed and in addition usually contains more abundant plant remains. It is generally yellowish buff in color where exposed in outcrop. Careful search within the first hundred feet above the ash bed will nearly always reveal specimens of the well known *Pecten peckhami* Gabb. The lower limit of the ash bed is not as easily determined in the field. No distinct contact exists between underlying argillaceous beds and shale of apparently the same character containing pyroclastic material. Thin sections show that the total thickness of such deposition in a section exposed at Lakeview along the Ventura River is about 14 feet. In the upper portion of the 14 foot section two layers, 30 inches and 10 inches respectively, are now bentonite. These were probably at one time almost exclusively volcanic ash. The other portions of the ash bed are made up of mixed material containing both argillaceous and sandy particles intermingled with glass shards, lava fragments and plant remains. The total thickness of the volcanic ash is probably much greater in area outside of the Ventura quadrangle. Dr. W. S. W. Kew stated during a field trip in the summer of 1929 that he had observed an ash bed of over 100 feet in thickness in the Santa Maria district about 70 miles north of Ventura.

Bentonite has been collected in the Ventura quadrangle at localities indicated on the sketch map, Fig. 1. It also occurs

[5] The Rincon formation constitutes a sequence of gray shale containing concretionary dolomitic layers, and lies between the Modelo formation (Lower Upper Miocene) and the Vaqueros formation (Lower Miocene). It is approximately 2150 feet in thickness as exposed in a type section along Los Sauces Creek east of Rincon Mountain. The Rincon formation has not heretofore been mentioned in the literature, although suggested in manuscript form at a recent meeting of local petroleum geologists in Los Angeles. A description of the formation, together with its distribution in the Ventura quadrangle, is now in preparation.

in other intermediate points where the soil cover has been removed. It is generally poorly exposed and in some instances is discovered with difficulty unless one follows the structural conditions of the district. The best exposures yet observed within the quadrangle may be listed as follows: (1) in a brick quarry at the mouth of Rincon Creek just north of the State Highway; (2) along the Ventura River at Oakview; (3) along the Southern Pacific R. R. right of way (Ventura-Ojai branch) three fourths of a mile south of Oakview; (4) on the west river bank of the Ventura River about 2 miles north of the Ventura Avenue oil field; (5) along Los Sauces Creek, 2 miles north of the Rincon oil field.

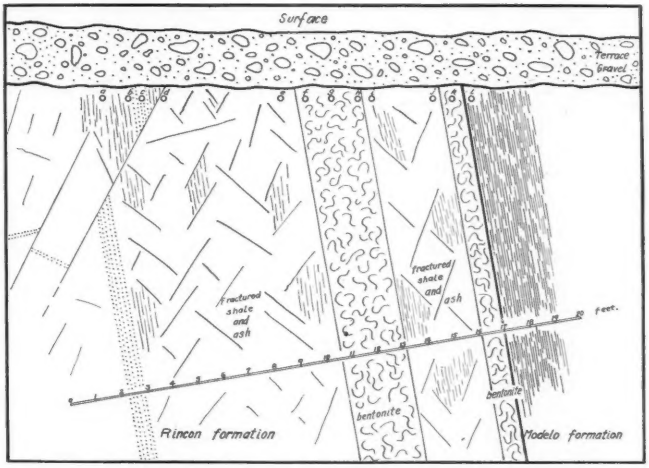

FIG. 2. An occurrence of bentonite on the east bank of Ventura River near Oakview. Strata strike N. 85° W. and dip 80° south. Two beds of bentonite are intercalated with volcanic ash and argillaceous shale. Capping the outcrop is an unconformable layer of Quarternary gravel.

The most satisfactory exposure is at Oakview. The occurrence is illustrated in a detailed section, Fig. 2. The bentonite occurs in two almost vertical layers at the contact between the Modelo

formation and the Rincon formation. The two formations are exposed for several hundred feet along the east river bank of the Ventura River. Overlying the strata unconformably is a poorly sorted covering of Quaternary gravel. The portion of the Modelo formation stratigraphically above the bentonite consists of an indurated, buff, platy shale richly foraminiferal and containing abundant plant remains. It also contains diatoms, but is essentially not as diatomaceous as would be expected in such a shale occurring in California. The strata have been badly fractured and tilted to a high angle. The strike is N. 85° W. and the dip is 80° S.

Samples were collected for microscopic study at positions marked *a* to *l* on the section. Specimens *a* to *e* consist of shale and buff colored calcareous sandstone marking the top of the Rincon formation. Specimens *d* and *e* were found to be volcanic ash mixed with fine grained sediment. Specimens *f*, *g*, *h*, and *k* were collected from bentonitic clay. Specimens *i* and *j* are fine fractured shale and pyroclastic material.

THE DEFINITION OF BENTONITE.

The name bentonite was first recorded in 1898 by W. C. Knight.[6] It was applied to a clay occurring in beds throughout several counties in eastern Wyoming. The clay had previously been named Taylorite in honor of William Taylor of Rock Creek, Wyoming, who brought it to notice. The name Taylorite, however, was discovered by Knight to be preoccupied, and consequently the term bentonite was substituted. As described by Knight the bentonite beds measured 4 to 5 feet in thickness and belonged to the Ft. Benton group of the Cretaceous.

Since the time of the original description, the significance of the word bentonite has changed considerably. On account of the resemblance between bentonite and various other types of clay, both in appearance and physical properties, questions have often arisen concerning the correct classification of all such material. In an attempt to clarify a somewhat confused situation, Ross and

[6] Knight, W. C., "Bentonite," *Eng. and Min. Jour.*, vol. 66, p. 491, Oct. 22, 1898.

Shannon[7] in 1926 proposed a re-definition of bentonite as follows:

> Bentonite is a *rock* composed essentially of a crystalline clay-like mineral formed by devitrification and the accompanying chemical alteration of a glassy igneous material, usually a tuff or volcanic ash; . . . the characteristic clay-like mineral has a micaceous habit and facile cleavage, high birefringence and a texture inherited from volcanic tuff or ash, and it is usually the mineral montmorillonite,[8] but less often beidelite.

Ross and Shannon studied bentonite from Wyoming among other samples, and found the mineral montmorillonite to be present in that clay. In addition, field observations show that the Wyoming clay was originally a volcanic ash.[9] The re-definition, therefore, would apply to the original clay, and the significance of the word bentonite would appear to be no longer in doubt.

The clay from Ventura has been examined from this point of view. It has been called bentonite only after having been shown to satisfy each of the requirements laid down in the above definition.

EXAMINATION OF THE VENTURA BENTONITE.

The bentonite forms a soft, soapy clay with a slight greenish cast. It is covered with an air-slacked layer of light gray powder which forms the best surface indication of its presence. The dried layer is usually several inches in thickness and beneath it the bentonite is invariably compact and moist, even toward the close of a dry summer. Specimens were collected in the moist condition and sealed in air tight jars. Such a sample when air-dried in small lumps becomes compact and hard, turning white in color. The dried lumps, when immersed in water, swell to more

[7] Ross, Clarence S., and Shannon, Earl V., "The Minerals of Bentonite and Related Clays and Their Physical Properties," *Jour. Amer. Ceram. Soc.*, vol. 9, no. 2, p. 79, Feb., 1926.

[8] It is now known that montmorillonite is identical with at least two other clay minerals known before montmorillonite was first described. The word montmorillonite, however, is now so firmly fixed in mineralogical literature that it would appear less confusing to let it stand than to attempt to establish the priority of the earlier names.

[9] Colony, R. J., "Personal Communication Based upon Field Work with Classes in Southeastern Wyoming."

than twice their original size. The moist clay, however, shows no tendency to swell in water but forms a soft slimy mass.

Thin sections of the Ventura bentonite show well defined relict bogen structure (Fig. 3). Shards and "bows" originally glass, have been replaced either in whole or in part by montmorillonite.

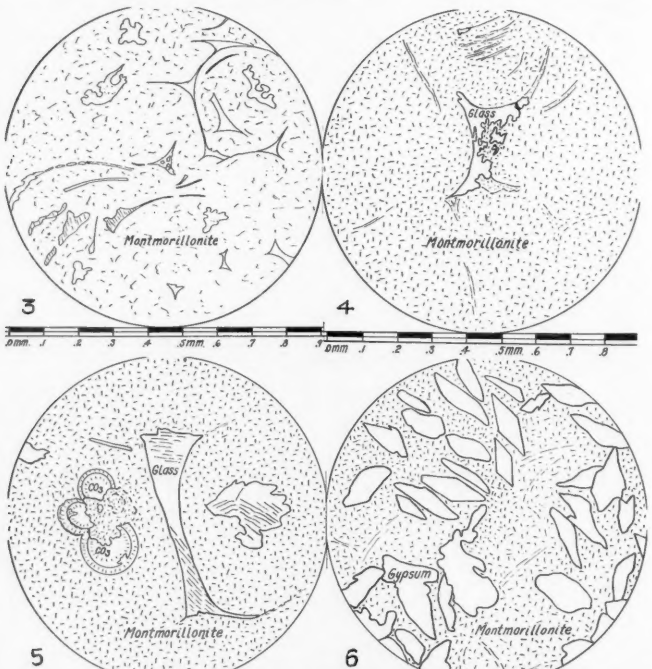

FIG. 3. Bogen structure in bentonite. Shards of volcanic glass are scattered through a matrix of montmorillonite.

FIG. 4. A shard of glass partially replaced by montmorillonite, as it may be seen in places in bentonite from the Ventura quadrangle.

FIG. 5. Foraminifera occur in places in the ground mass of the bentonite. The sections are composed of calcite in part replaced by montmorillonite.

FIG. 6. Gypsum crystals are abundant in some portions of the bentonite.

An example of a partly replaced shard is shown in Fig. 4. Thin sections show all stages of devitrification from the partly replaced shards as shown in Fig. 4 to a ground mass of montmorillonite with only "ghosts" of shards. Montmorillonite also fills the interiors of the contraction curves. In thin sections cut from specimens collected along the margins of a bentonite bed the shards are mainly rhyolitic glass with some alteration to zeolite. Flow lines are still in evidence in places in the glass. Microscopic study of sections from the center of a bentonite bed shows that the clay is composed almost entirely of montmorillonite and the bogen structure has been largely destroyed. Such evidence would seem to indicate that devitrification has been more complete in the centers of the beds than along the margins.

The microscopic structure of the clay furnishes the best criterion of bentonitic origin. The structures observed are all of a typically pyroclastic nature. It is interesting to note, however, that in addition to the pyroclastic structures thin sections show frequent cross-sections of foraminifera and occasional diatoms (Fig. 5). The foraminiferal remnants are in part calcareous although replaced to some extent by montmorillonite. The few diatom casts present are made up of opal.

Organic material is present in both the bentonite and adjacent sedimentary beds. It appears particularly abundant in thin sections cut from the lower portion of the Modelo formation and also from the strata immediately underlying the bentonite. Sections of mixed volcanic ash and sediment show an abundance of zeolitization. A weakly birefringent, platy zeolite, with indices of refraction corresponding to heulandite, is prominent.

The essential clay mineral constituent of the bentonite is finely crystalline. It is characterized by a micaceous structure and distinguished from other clay minerals by a high birefringence. It varies in optical properties according to the amount of adsorbed water. Specimens collected in a moist condition and kept moist in a sealed glass jar had both a lower refractive index and a lower birefringence than air-dried samples of the same clay. The optical constants of the moist clay were $n_\alpha = 1.470$, $n_\gamma = 1.481$, double refraction .011; and of the air-dried clay, $n_\alpha = 1.510$, $n_\gamma = 1.532$, double refraction .022. The optical properties of

the dried clay mineral agree within reasonable limits with those given by Ross and Shannon for montmorillonite.[10]

Gypsum crystals line seams of clay in a number of places. A cluster of such crystals in a matrix of montmorillonite may be seen in Fig. 6.

The residue left after washing the clay contains gypsum, quartz, orthoclase, oligoclase, glass, zircon, and octahedrite. Quartz, feldspar, and glass occur in angular fragments in both thin sections and in the residue from washing. Gypsum occurs in misshapen crystals prominently distributed through the bentonite. Both zircon and octahedrite appear only in the residue but are nevertheless abundant. The crystals of each are unusually sharp.

CHEMICAL ANALYSIS.

A sample of air-dried clay from the center of the 30-inch Oakview clay bed was purified by suspending in water. The suspended portion was left standing until microscopic examination showed it to be practically free from mechanical impurities of microscopic size. A sample was then collected for chemical analysis. The analysis of the clay by Mr. A. M. Smoot of Ledoux and Co. is as follows:

	Ventura Bentonite
	%
Water at 105° C.	12.80
Water + 105° C.	5.01
Total water	17.81
SiO_2	57.62
Al_2O_3	15.01
Fe_2O_3	1.97
FeO	0.41
CaO	2.84
MgO	3.60
TiO_2	0.20
K_2O	0.03
Na_2O	0.05
P_2O_5	0.09
CO_2	0.48
Zr, Mn, SO_3	none
Total	100.11

[10] *Op. cit.*

The analysis agrees within reasonable limits with analyses of montmorillonite-bearing bentonites, given by Ross and Shannon.[11] The silica content, however, is higher than the average and the water is proportionately low. A certain amount of extra silica may be present, due to finely divided opal derived from silica-secreting organisms and not removed during the purification of the clay. On the other hand the high silica content may be normal for a bentonite derived from such a highly siliceous rock. The exact status of the extra silica is not certain. The calcium oxide and magnesium oxide are present in about correct proportions for montmorillonite. The presence of a small amount of carbon dioxide indicates that all of the calcite-bearing foraminiferal fragments were not removed during purification. The calcium oxide figure is, therefore, not entirely due to calcium oxide from the mineral montmorillonite.

Whether the iron oxide is actually a part of the formula for montmorillonite in the Ventura bentonite or should be attributed to inseparable impurities of size beyond microscopic range is uncertain. Microscopic examination of the purified material shows no free particles which would be expected to carry iron oxide. On the other hand some members of the montmorillonite group, which optical and x-ray examination indicates are not nontronite, yield iron oxide on analysis, apparently due to adsorbed iron. Stained areas in thin sections may be indicative of such phenomena.

The fractional per cent. of alkali present is significant. It indicates almost complete removal of the alkali elements during the transition from volcanic ash to bentonite.

The moisture content of the bentonite is considerably below the theoretical value for montmorillonite, although not too low to be within the bentonite range. If either explanation of the high silica content outlined above is accepted, the percentage of moisture would be low. The exact status of water in bentonite, however, still presents a problem.

[11] *Op. cit.*, pp. 88–89.

X-RAY EXAMINATION OF VENTURA BENTONITE.

X-ray diffraction patterns of clay minerals furnish a convenient and probably one of the most accurate means available for their classification. X-ray diffraction measurements for minerals of the kaolin group are already on record.[12] Such measurements coupled with optical and chemical data show the so-called kaolin minerals to differ from the clay mineral constituents of bentonite. The latter material, as shown by the optical and chemical work of Ross and Shannon, is composed essentially of either montmorillonite or beidellite. X-ray examination of the clay samples studied by Ross and Shannon confirms their conclusions. X-ray diffraction patterns of type montmorillonite from Montmorillon, France, agree with the pattern of the essential constituents of the bentonites. Beidellite would appear from x-ray data to be closely related to montmorillonite structurally. In fact, definite distinction between montmorillonite and beidellite by x-ray diffraction patterns has not yet been accomplished.

The patterns of montmorillonite and beidellite are unfortunately poorly developed in contrast to patterns given by other clay materials. The lines are generally too few in number and somewhat diffused. In consequence, x-ray diffraction patterns of the montmorillonite group, although distinctive from patterns of other clay materials, do not offer reliable criteria in themselves for definite distinction between all the members of the group. The reason for the character of pattern lies in the extremely fine dimensions of the montmorillonite crystals. It is well known that x-ray patterns of such a finely crystalline mass lack the development of those given by more coarsely crystalline substances.

Although the montmorillonite pattern is not comparable to the patterns of the kaolin type, it is sufficiently characteristic to distinguish from the kaolin materials, and other clay minerals. When optical and chemical work are carried out in conjunction with x-ray work, the identification may be considered complete.

[12] Ross, Clarence S., and Kerr, Paul F., "The Kaolin Minerals," *Jour. Amer. Ceram. Soc.*, vol. 13, no. 3, p. 151, March, 1930.

In the case of an x-ray examination of forty samples of members of the montmorillonite group from different localities, the x-ray study has been found to confirm the chemical analysis and optical investigation in each instance. A complete description of the montmorillonite group is being prepared in coöperation with Dr. C. S. Ross, of the U. S. Geological Survey, and will appear at a later date.

X-ray study of the Ventura bentonite was carried out in order to determine whether the clay contained a crystalline constituent corresponding to montmorillonite. An x-ray diffraction pattern was taken with an exposure of 18 hours at 15 M.A. and 30 KVrms, utilizing the Kα radiation of molybdenum.[13]

The x-ray diffraction measurements of the Ventura bentonite are given in Table 1. The x-ray diffraction pattern of Ventura bentonite is shown by diagram in Fig. 7. Similar diagrams of

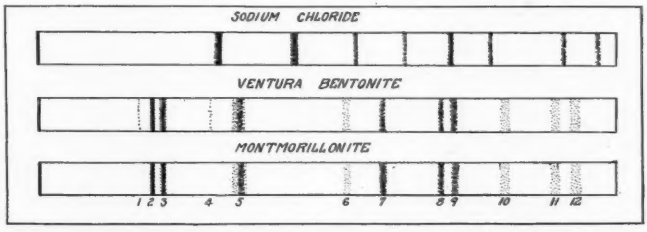

FIG. 7. A diagram illustrating the x-ray diffraction pattern of Ventura bentonite. Similar diagrams of sodium chloride and montmorillonite from Montmorillon, France, with equal x-ray exposure are illustrated above and below respectively.

sodium chloride (given for reference) and montmorillonite from Montmorillon, France, are also shown. The three patterns illustrated were taken under closely corresponding conditions of exposure, in fact the sodium chloride and the Ventura bentonite patterns were taken side by side in the same casette. Numbers appear below the Montmorillonite pattern corresponding to the lines present in the patterns of the two clays.

[13] Kerr, P. F., "The Determination of Opaque Ore-minerals by X-ray Diffraction Patterns," ECON. GEOL., vol. 19, pp. 1–34, Jan., 1924.

The Ventura bentonite and montmorillonite patterns are identical both in spacing and intensity in the case of all lines except numbers 1 and 4. These two lines do not appear in the montmorillonite pattern as exposed. Six different patterns of montmorillonite from the type locality with varying exposure were examined as standards for comparison.

TABLE I.

MEASUREMENT OF THE X-RAY DIFFRACTION PATTERN OF VENTURA BENTONITE.

Ventura Bentonite.			Comparison with NaCl.		
Line No.	Outer Edge in m.m. from Zero Beam.	Spacing in A.U. = $\times 10^{-8}$ cm.	Line from Planes.	Outer Edge in m.m. from Zero Beam.	Spacing in A.U. = $\times 10^{-8}$ cm.
1	16.1	5.36			
2	18.3	4.49			
3	20.2	4.05			
4	27.4	2.99			
			(100)	28.9	2.814
5	33.0	2.48			
			(110)	41.2	1.990
6	49.2	1.67			
			(111)	50.4	1.624
7	56.1	1.47			
			(100) n = 2	57.8	1.407
8	64.2	1.29			
			(210)	65.35	1.258
9	66.2	1.250			
			(211)	71.81	1.148
10	74.7	1.115			
11	82.0	1.020			
			(110) n = 2	83.25	.996
12	85.6	.976			
			(221) or (100) n = 2	88.75	.937

Table I. gives the approximate spacing in Angstrom Units for the lines of the x-ray diffraction pattern of Ventura bentonite. Similar measurements for the first eight lines of sodium chloride are also given for comparison.

The above discrepancy between the two patterns may be attributed either to the presence of impurities in the sample of Ventura bentonite or to the fact that the clay constituent is a slightly different modification of the montmorillonite group. In view of the weakness of the lines and corresponding uncertainty in their measurement the latter alternative seems hardly justified; par-

ticularly since optical and chemical work fail to support such a conclusion. Experience gained from a study of a large number of bentonite patterns would lead to the conclusion that the Ventura bentonite gives an x-ray diffraction pattern of the montmorillonite type with two faint traces of lines due to impurities.

ORIGIN OF VENTURA BENTONITE.

The sequence of events leading to the formation of the bentonite as it is now found in the Ventura quadrangle is reasonably clear. The presence of foraminifera and diatoms signifies a marine origin of the entire thickness of strata in which the bentonite is found. Studies of local geology also show that the strata are of marine origin without material unconformity for 2500 feet below the bentonite horizon and for a greater thickness above. The deposition of the sediment containing the ash probably occurred in shallow water, judging from the abundance of plant remains.

The fact of igneous activity in California in the coastal region in Miocene time is well known. Considerable areas of igneous rocks may be found between Ventura and Los Angeles and also in the Coast Ranges to the north. The same sources furnishing these rocks may have been responsible for a widespread deposition of volcanic ash. The center of volcanism responsible for the ash deposited in the Ventura quadrangle is uncertain. The conditions of deposition of the bed now bentonite, however, appear more clearly outlined. It may be assumed in conclusion that the bentonite has been derived from a volcanic ash deposited in shallow marine water, probably in Lower Upper-Miocene time.

SUMMARY.

A light olive green soapy clay occurs in a number of places in Miocene strata of the southern California Coast Ranges. In the Ventura quadrangle it marks the contact between the Rincon formation and the Modelo formation, two formations important because of their relationship to petroleum production. Samples of the clay were collected from several localities in which the field

relations were known. These have been submitted to laboratory study involving joint optical examination, chemical analysis and x-ray investigation. According to the various methods of study, the essential constituent of the clay is the mineral montmorillonite. Relict structures observed in thin sections show that the clay is bentonite.

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A CLASSIFICATION OF THE LODE DEPOSITS OF SOUTH-CENTRAL IDAHO.[1]

CLYDE P. ROSS.

CONTENTS.

	Page
Foreword	169
Summary of geology	173
The classification	174
The outline	174
Class 1, Group 1	175
Class 1, Group 2	178
Class 1, Groups 3 and 4	178
Scarcity of zonal relations in Class 1	179
Class 2, Groups 1 and 2	181
Class 2, Group 3	182
Class 2, Group 4	182
Distribution of the lodes of Class 2	183
General economic features	184

FOREWORD.

THE casual observer is so impressed by the diversity of characteristics in the ore deposits of south-central Idaho that classification appears impractical. Closer study, however, shows that the diversity is largely in details, and the geologic features and relationships of the lodes permit them to be segregated into two main classes, each class divisible into four groups, each group in turn divisible into one or more subgroups as shown on the accompanying chart (Table I.). With few exceptions, mostly of minor economic importance, replacement played a dominant part in the genesis of the lodes of the region.

The classification here presented is one of the results of a study of the ore deposits of south-central Idaho which was

[1] Published by permission of the Director, U. S. Geological Survey. Presented before the Society of Economic Geologists, Charlottesville, May, 1930.

TABLE I.

CLASSIFICATION OF LODE DEPOSITS OF SOUTH-CENTRAL IDAHO.

(Subdivisions are arranged in order of economic value. Mineral lists are diagnostic but not complete.)

I. DEPOSITS RELATED TO MESOZOIC IGNEOUS ROCK.

A. Deposits in Shear Zones in Siliceous Rocks.

1. *Ore:* Massive sulphides (galena, with tetrahedrite, chalcopyrite, sphalerite, and arsenopyrite).
   Gangue: Siderite with quartz.
   Type mines: Mayflower and War Dance, Wood River District; Ramshorn, Bayhorse District.
2. *Ore:* Massive sulphides (jamesonite, galena).
   Gangue: Quartz, calcite.
   Type mine: Livingston, in Custer County.
3. *Ore:* Disseminated sulpharsenides and antimonides; Ruby silver, minor pyrite, and galena.
   Gangue: Quartz with some siderite.
   Type mine: Vienna, in Blaine County.
4. *Ore:* Auriferous pyrite, generally with other sulphides.
   Gangue: Quartz and sericitized rock.
   Type mine: Boise-Rochester in Atlanta District.
5. *Ore:* Chalcopyrite.
   Gangue: Quartz, micas.
   Type mine: Pope-Shenon, in Lemhi County.
6. *Ore:* Hubnerite with some other metallic minerals.
   Gangue: Quartz.
   Type mine: Patterson, in Lemhi County.
7. *Ore:* Cobalt, nickel, and copper minerals.
   Gangue: Quartz, tourmaline, etc.
   Type mine: Haynes-Stellite, in Blackbird District.

B. Irregular Replacement Deposits in Calcareous Rocks.

1. *Ore:* Galena, sphalerite.
   Gangue: Quartz, calcite, no silicates.
   Type mine: Red Bird, Bayhorse District.

C. Contact Metamorphic Deposits.

1. *Ore:* Galena, chalcopyrite.
   Gangue: Silicates.
   Type mine: Phi Kappa, in Custer County.
2. *Ore:* Magnetite, little gold.
   Gangue: Silicates.
   Type mine: Iron Clad, Wood River District.

D. Pegmatitic Veins.

1. *Ore:* Molybdenite.
   Gangue: Quartz, feldspar.
   Type mine: Rinebold, in Rocky Bar District.

2. *Ore:* Disseminated pyrite, with a little galena and other common sulphides.
Gangue: White quartz.
Type mine: Blue Rock, in Boise Basin.

II. DEPOSITS RELATED TO TERTIARY IGNEOUS ROCK.

A. Banded Veins in Tertiary Volcanics.

1. *Ore:* Gold, silver, mainly in microscopic grains of selenide.
Gangue: Fine-grained quartz.
Type mine: General Custer, in Yankee Fork District.
2. *Ore:* Galena, sphalerite, and minor amounts of numerous other metallic minerals; oxidized silver minerals, profitable.
Gangue: Quartz with calcite and other carbonates.
Type mine: Hub, in Lava Creek District.

B. Lodes without Sharp Boundaries in Tertiary Volcanics.

1. *Ore:* Disseminated gold, silver.
Gangue: Fine-grained quartz, clay minerals.
Type mine: Sunnyside, in Thunder Mountain District.
2. *Ore:* Stibnite.
Gangue: Barite.
Type mine: Prospect, at Meyers Cove.

C. Contact Metamorphic Deposits.

1. *Ore;* Chalcopyrite or sphalerite.
Gangue: Silicates.
Type mine: Empire, in Mackay District.
2. *Ore:* Pyrite, pyrrhotite, lollingite.
Gangue: Silicates.
Type mine: Flux quarries, in Loon Creek District.

D. Deposits Related to Tertiary Dikes.

1. *Ore:* Precious metals, bismuth, galena, pyrite.
Gangue: Quartz.
Type mine: Belshazzar, in Boise Basin District.
2. *Ore:* Cinnabar.
Gangue: Quartz, altered rock.
Type mine: Hermes, in Yellow Pine District.

begun in 1923 and has been carried on continuously since then. During this time nearly all the mining districts in Blaine, Boise, Butte, Camas, Custer, Elmore, and Lemhi Counties, and that part of Idaho County which lies south of the Salmon River, have been visited and many of the mines and prospects, especially in Blaine, Custer, and Lemhi Counties, studied with care. Published reports and other data have been freely

consulted to supplement personal observation. The data thus assembled are too voluminous for adequate summary in the present paper, especially as much of the writer's work is still unpublished, but will be found in reports on specific districts (published and in preparation) and will be summarized in a general report on the geology and ore deposits of the region now in preparation for the U. S. Geological Survey in coöperation with the Idaho Bureau of Mines and Geology. This paper presents the classification in outline, emphasizing its features of economic significance. Suggestions regarding it from those familiar with the mines of the region will be welcomed. More complete treatment must await the general report.

The classification here adopted is essentially a genetic one, based primarily on source, secondarily on form and method of deposition, and finally on mineral content. The subdivisions under each heading are arranged in order of economic importance. Knowledge of the general geology of the region and of the majority of the ore deposits is sufficiently comprehensive to give assurance that a classification founded on these data will be fundamentally sound, although the genesis of certain ore deposits, mostly of minor commercial interest, must remain in doubt until further data are available. It has been suggested [2] that pre-Jurassic ore deposits may exist west of the region under consideration; if so, a third major class should be added to the classification here proposed. As in most classifications of natural phenomena, there is a certain amount of gradation among the different subdivisions. Certain individual deposits may exhibit characteristics of different groups or subgroups, making their proper assignment a matter of judgment, but only a few deposits in the region present any considerable difficulty in classification on this account. The classification here proposed is subject to modification and is susceptible of expansion in detail.

[2] Livingston, D. C., "A Geologic Reconnaissance of the Mineral and Cuddy Mountain Mining Districts, Washington and Adams Counties, Idaho," Idaho Bureau of Mines and Geology, Pamphlet 13, p. 19 (no date). Gilluly, James, "Copper Deposits in the Keating District, Oregon." In preparation.

SUMMARY OF GEOLOGY.

As the classification is based mainly on the origin of the ores, a geologic problem, a summary of the geology of the region is essential to a clear presentation of the subject. Much or all of south-central Idaho in Algonkian time was covered by a shallow sea in which clastic deposits accumulated to great thicknesses, presumably on a gradually subsiding sea floor. Since that time the history of the region has been mainly one of intermittent uplift accompanied by igneous intrusion. The Algonkian deposits were early converted into the quartzites, argillaceous quartzites, and limestones of the Belt series. They are cut by metamorphosed diabasic dikes probably likewise of Algonkian age.

Throughout Paleozoic time the eastern part of the region was intermittently covered by somewhat deeper seas, and material now converted into quartzites, argillites, dolomites, and marbles totalling tens of thousands of feet in thickness was laid down. The Paleozoic seas appear to have rarely extended westward into the area now occupied by the exposed portions of the Idaho batholith. This was a positive area even then, although the intrusion of the great batholith did not take place earlier than the Jurassic. Intensive volcanic activity, at least in part submarine, marked the Permian in eastern Oregon and western Idaho, and thousands of feet of andesites and other lavas and fossiliferous tuffs accumulated. The presence of similar rocks in south-central Idaho, though void of fossiliferous beds, indicates that the volcanism of this period extended widely over this region also.

South-central Idaho appears to have been dry land continuously since the Permian, although Mesozoic seas existed both east and west of it. In the later part of the Mesozoic, probably starting in the Jurassic, there were profound orogenic disturbances accompanied by the intrusion of the Idaho batholith of quartz monzonite and related rocks, to which the majority of the ore deposits of the region are genetically related. Deformation was more intense and intrusion took

place on a greater scale than at any other time in the history of the region, although there is comparatively obscure evidence of several earlier diastrophic disturbances.

Volcanism on a grand scale occurred in Tertiary time, probably Miocene for the most part, and resulted in the accumulation over most of the region of lavas and pyroclastic rocks with a total thickness of fully a mile. These rocks range from basalt to rhyolite, but in large part have the composition of quartz latite. Late in this period of igneous activity the flows were flexed and broken and, together with the older rocks, were intruded by several bodies of granite, whose axes tend to follow structural axes in the inclosing rocks, and by many dikes of diverse compositions, largely granophyric. This intrusive activity, like the previous one, was accompanied by the formation of ore deposits.

The Pliocene and Pleistocene basaltic effusions characteristic of the Snake River Plain nowhere extended far into the mountain region, unless some of the basalt in Custer County is as young as Pliocene. The Quaternary in south-central Idaho has been essentially a time of uplift accompanied and followed by stream and glacial erosion. During it placers have formed and in many places oxidized parts of lodes have been swept away.

THE CLASSIFICATION.

The Outline.—The essential features of the classification here proposed are given in Table I. The lodes are divided into two classes corresponding to the two periods of igneous activity in which they were formed. Each class is divided into four groups based on form and mode of origin, and all but one of the groups are further subdivided into subgroups according to essential mineral composition. The subgroups are susceptible of modification and further subdivision if increase in knowledge or the requirements of some particular purpose make it desirable. The subdivisions are numbered in the order of their economic importance, which is based upon past and present activity and probable reserves. Since most of the

present mining is in lodes belonging to Class 1, the arrangement in Class 2 is relatively tentative. The lists of minerals given in each subgroup in the chart are intended to be diagnostic but are by no means complete. Such common minerals as pyrite, for example, are present to some extent in many of the subgroups, but are mentioned on the chart only where they are characteristic.

Mines typical of each subgroup are listed on the chart. Most of those chosen are well known to the mining men of Idaho, but of necessity some of the subgroups of minor economic value are represented by prospects or small mines. The name of either the mining district or county in which each mine occurs is also given, depending on which is likely to be most useful in identification.

Class 1, Group 1.—At present, all the more productive mines with the exception of the Empire copper mine near Mackay, and a few precious metal properties in Boise Basin, are in deposits of class 1, group 1, and the majority are in subgroup 1 of that group. The shear zones characteristic of this group were produced by the most intense orogenic activity to which the region is known to have been subjected and were, at least in large part, the result of compressive stresses acting at considerable depths. They are likely, therefore, to have greater continuity than openings formed in Tertiary time under smaller, largely tensional stresses, at shallower depths.

It is a well-known feature of the ore deposits of class 1 in this part of Idaho that the known ore tends to cease at shallow depths. Numerous lodes have been apparently bottomed within 200 feet of the surface and mines as much as 1000 feet deep are rare. However, good evidence exists, especially in the Wood River region,[3] that the lodes go deeper than the known ore shoots, and the existence of additional shoots at greater depths is probable, although the present paucity of clues makes their discovery difficult. The genesis and character of the lodes of group 1, especially in subgroups 1 and 5,

[3] Umpleby, J. B., Westgate, L. G., and Ross, C. P., "Geology and Ore Deposits of the Wood River Region, Idaho," U. S. Geol. Survey Bull. 814, pp. 101–105, 1930.

are such as to make it improbable that they are restricted within narrow vertical limits.

The larger ore shoots in the lodes of the first three subgroups, with some exceptions, dip 45° and less, so that, in spite of the shallow depth to which many have been followed, pitch lengths of 1000 feet are rather common, especially in subgroup 1. Many of the developed shoots are several hundred feet long and from a few feet to over 20 feet wide.

The deposits of subgroup 1 are characterized by abundant siderite (unlike all the other subgroups) and commonly contain argentiferous galena, but the proportions of the other metallic minerals vary greatly. Tetrahedrite (generally the argentiferous variety, freibergite) is fairly common, but ore shoots in which it is the mineral of major economic value, as in part of the Ramshorn mine, are exceptional. Locally copper, zinc, or arsenic is abundant in lodes of this subgroup but none of these metals has yet been sought extensively, although advances in metallurgy have recently attracted attention to some of the complex ores that contain them.

Subgroup 2 is represented, so far as known, by a few lodes in southern Custer County, of which the well-known Livingston Mine is the only one that has yet attained any considerable production. Structurally, and in their areal proximity to the Idaho batholith, they resemble subgroup 1. Although mineralogically they differ from other lodes in class 1, their intimate association with border facies of the Idaho batholith, especially with aplite dikes, appears to warrant their assignment to this class.

Up to the present, the lodes of subgroup 3 have been valuable for small but fairly rich bodies of silver ore in which proustite and pyrargyrite were the predominant metallic minerals. Recently in the Vienna District [4] lower-grade lead and zinc ores, worthless to the early miners, have been developed in lodes of this subgroup. These ore minerals and the accompanying siderite link subgroup 3 to subgroup 1.

[4] Ross, C. P., "The Vienna District, Blaine County, Idaho," Idaho Bur. of Mines and Geology Pamphlet.

The presence of similar sulpharsenides and sulphantimonides in some of the lodes of subgroup 4, especially in the Atlanta District,[5] forms a link between this group and subgroup 3. Although the possibility of profitably mining the base metal ore tends to increase the potential value of lodes of subgroup 3, their small size makes them less attractive to the larger companies than to individual operators or lessees, who can hope for occasional rich rewards in the shape of pockets of high-grade silver ore.

Subgroup 4 includes most, if not all, of the precious metal lodes in Elmore, Valley, and southern Idaho Counties and probably some of those in Boise County. The lodes more nearly approximate the popular conception of "true fissure veins" than most of the others in the region since they generally contain lenses of massive quartz; but parallel lenses are characteristic, and much of the ore is in the sheared and altered country rock bordering the quartz lenses. Sericitization of the wall rock, which is generally granitic, and the relative paucity of metallic minerals are characteristic. In the early days, considerable gold and silver was mined from pockets in the upper portions of these lodes, but their future value lies in their development as large but low-grade precious metal deposits. A number of them are 200 feet and more wide and continuous for thousands of feet along the strike, but, except for rare pockets, assays as high as $10 a ton are exceptional and much of the ore in the larger lodes probably averages materially less than $3 a ton in gold and silver.[5a] The lodes commonly contain some base metals, but, except for some shoots of copper ore, the quantity present is generally too small to be of value to the miner.

Subgroup 5 comprises rather indefinitely bounded lodes in which much of the gangue is altered country rock (mainly Belt argillaceous quartzite) and essentially the only valuable metal is copper. The average tenor of ore thus mined is 2½ to 6 per cent. copper and the ore shoots have lengths up to

[5] Ballard, S. M., "Geology and Ore Deposits of the Rocky Bar Quadrangle," Idaho Bur. of Mines and Geol. Pamphlet 26, p. 17, 1928.

[5a] There are, however, certain narrow veins falling approximately in this subgroup that contain ore shoots averaging $20 and more in gold and silver.

several hundred feet and widths from a few inches to 20 feet or more.

Subgroups 6 and 7 comprise small low-grade deposits, none of which are being worked at present or have any considerable production record. Subgroup 6 [6] resembles subgroup 5 except that the lodes are much smaller and tungsten is the principal asset, although copper, molybdenum, and other metals are locally present. Subgroup 7 comprises irregular deposits of metasomatic origin that have not yet been extensively developed nor geologically studied in detail.[7] Unlike most of the deposits here placed in class 1, there is no known direct evidence as to the period of igneous activity to which they belong. Intrusive rocks of pre-Cambrian, Mesozoic, and Tertiary age exist in the general vicinity, but the most probable inference is that the lodes are of Mesozoic age.

Class 1, Group 2.—The major difference between group 1 and group 2 is that the deposits of group 2 are in relatively replaceable calcareous or dolomitic instead of siliceous rock. The deposits of group 2 are consequently irregular in shape, and individual shoots rarely exceed a few score feet in any dimension. Many shoots contain lead-silver ore of excellent grade (generally with recoverable zinc). Favorable structural conditions have in places, as at the Red Bird, resulted in so localizing the deposits that large total production has been obtained from an aggregate of individually rather small shoots. The group in general, however, contains numerous prospects but relatively few mines.

Class 1, Groups 3 and 4.—Up to the present no mines of consequence have been developed in groups 3 and 4. There is some gradation between groups 2 and 3, but in general the distinction is valid and easy to make. The lodes of group 3 are characterized by the presence of lime-silicates in impure

[6] Umpleby, J. B., "Geology and Ore Deposits of Lemhi County, Idaho," U. S. Geol. Survey Bull. 528, pp. 109–112, 1913. Livingston, D. C., "Tungsten, Cinnabar, Manganese, Molybdenum, and Tin Deposits of Idaho," School of Mines, University of Idaho, Bull. 2, pp. 21–25, 1919.

[7] Hess, F. L., "Cobalt," Mineral Resources of the United States, 1917, Pt. 1, pp. 899–901, 1921.

calcareous rock and are thus linked with some of the lodes of group 1, which are bordered by wall-rocks containing lime-silicates. Group 3, subgroup 1, has yielded a small production but little or no profit, and subgroup 2 has been mined mainly where it was conveniently situated for use as ferruginous and calcareous smelter flux, the small gold content helping to pay handling costs. There has been essentially no production from group 4.

The relatively small size and scarcity of deposits of groups 3 and 4 emphasizes the fact that the magma of the Idaho batholith was relatively dry. Contact phenomena are characteristically restricted. In most places pegmatites are meagerly developed or absent, and aplites and lamprophyres are generally neither large nor abundant. The principal evidence of fluidity exhibited by rocks related to the Idaho batholith is in the injection gneiss which locally borders it.

Scarcity of Zonal Relations in Class 1.—It would seem that diversified, yet genetically closely related ore deposits distributed over a large area like those represented in class 1 should show evidence of zonal relations,[8] but this is true only to a very limited extent. The outstanding example of such spacial zoning, as Thomson and McGonigle [9] have pointed out, is the localization of most of the gold lodes within the borders of the main batholith, and most of the Mesozoic base metal lodes outside of it. Most of the gold lodes are in or close to detached roof pendants or close to the original margin of the granitic mass (the endobatholithic lodes of Emmons[10]). Some of them contain copper. Although erosion has been so shal-

[8] Emmons, W. H., "Primary Downward Changes in Ore Deposits," *Trans. Amer. Inst. Min. and Met. Eng.*, Vol. 70, pp. 964–997, 1924. Spurr, J. E., "Ore Magmas." Emmons makes distinction between (1) zonal arrangement of metals within individual lodes or lode systems and (2) zonal grouping of deposits characterized by certain metals with reference to the igneous intrusions to which they are genetically related. With a few possible exceptions, there is no evidence of zoning of the first sort in the mines of the region, possibly in part because development in most of them is shallow.

[9] Thomson, F. A., and McGonigle, Fritz, "Zonal Distribution of Gold, Silver, Lead, and Copper Ores in Idaho," *Eng. and Min. Jour.*, Vol. 120, pp. 216–218, 1925.

[10] Emmons, W. H., "Relations of Metalliferous Lode System to Igneous Intrusions," *Trans. Am. Inst. Min. and Met. Engrs.*, Vol. 74, pp. 29–70, 1926.

low that it has left the gold lodes widely distributed over much of the Idaho batholith, it has, with few exceptions, removed any base metal lodes deposited at greater distances from the source of mineralization except those outside the present borders of the batholith. Where erosion of the batholith has been relatively deep, Mesozoic mineral deposits of any kind are scanty.

Most of the base metal deposits of the region are in sedimentary rocks at different distances from subsidiary granitic masses and at considerable distances from the main batholith. Some are many miles from any granitic rocks shown on existing maps. On the whole, they may be regarded as belonging to a poorly defined outer zone. In the southern part of the Wood River region, however, where some of the base metal lodes are near a local granitic stock, there is a tendency for them to divide into two minor zones, the lodes relatively high in zinc being found in or comparatively close to the stock and the lead lodes farther from it.

In addition to the gold lodes associated with the main batholith there is in Lemhi County a fairly large group of gold lodes which are in and near relatively small granitic masses of the same age as the Idaho batholith. Some of these lodes contain considerable copper and the group is areally associated with the copper lodes of group 1, subgroup 5, of the present classification. This subgroup includes all the productive copper deposits in class 1 except a few in group 1, subgroup 1, that were formerly productive. The sedimentary rocks near many of the copper deposits of both of these subgroups contain silicate minerals that indicate a considerable amount of igneous metamorphism—more than that characteristic of the rocks near most of the lead-silver deposits.

Most of the lead-silver deposits of the region are in sedimentary rocks at different distances from known granitic rocks, and some are many miles from them. On the whole, they may be regarded as belonging to a poorly defined outer zone deposited farther from the source than either the gold or copper lodes. In the southern part of the Wood River region

some of the lodes are grouped comparatively close to granitic masses and exhibit locally a spacial zoning, deposits high in zinc being found in or comparatively close to the granitic rock, and the lead lodes farther away.

A large proportion of the silver mines in class 1 belong to group 1, subgroup 3, and occur in the granitic rocks near the southeastern border of the Idaho batholith. Since it appears generally true that sulpharsenides and sulphantimonides of silver are deposited in the outermost zones from the source of mineralization, this position is anomalous.

Class 2, Groups 1 and 2.—The lodes in class 2, groups 1 and 2, include all those in or closely related to Miocene (?) volcanic strata. They are listed first because of their past production, especially in the Yankee Fork District, Custer County, and their low-grade reserves in the Thunder Mountain and other districts, although a few exceptional deposits in groups 3 and 4, such as the Empire Mine at Mackay, are at present more productive than any in the first two groups. The lodes of the formerly rich and famous Silver City District, Owyhee County, south of the region here considered, belong to group 1 and have many points of similarity to the lodes of that group in south-central Idaho. At present the easily accessible rich parts of the lodes of group 1 (in part resulting from supergene enrichment) have in large measure been exhausted and the lodes of group 2 have been tested and found in general to be too low grade for profitable operation under present conditions. Both groups, however, contain large bodies of ore averaging $5 a ton and less in precious metals, which may eventually prove valuable.

The first subgroup in each of these groups is similar to lodes of mid-Tertiary age elsewhere in the Rocky Mountain region. A gangue consisting mainly of altered lava or tuff and cryptocrystalline quartz contains sparsely disseminated free gold, with silver and fine-grained selenides of the precious metals. Parts of the local masses of rich ore are supergene, part hypogene. Such base metals as are present have not yet proved of value.

Subgroup 2 in the first group is represented by the Lava Creek District,[11] mainly in Butte County. The deposits are in part in Miocene (?) volcanics, in part in neighboring older rocks. They were formerly valuable for rich supergene silver ore, but the hypogene lead, zinc, copper, antimony, and tungsten deposits which remain have not been appreciably productive. Subgroup 2 in the second group is at present merely a mineralogical curiosity.

Class 2, Group 3.—The main economic interest in group 3 is in the exceptional deposits of the Alder Creek District, Custer County, which constitute the only known representatives of its subgroup 1. The Empire Mine in that district has been productive for many years and during much of its history has been the largest producer of copper in the State. The nearby Horseshoe Mine has yielded considerable lead carbonate ore, and contains an undetermined quantity of ferruginous sphalerite and other hypogene metallic minerals. The deposits of this type would be easily distinguishable from those of group 3 in class 1, even if the latter were found in similar dolomite, by their association with Tertiary granitic rock with its characteristic micropegmatite and generally pinkish color. Subgroup 2, like the corresponding subgroup in class 1, has been utilized to some extent as calcareous smelter flux, as it contains almost enough gold to pay handling costs. It is also of geological interest because of its relation to rather small dikes which appear to have served as conduits for emanations from a deeper-seated granitic body.

Class 2, Group 4.—The deposits related to Miocene (?) dikes have thus far received comparatively little study. As already noted, some of the dikes are related to contact-metamorphic deposits in calcareous rocks, but only lodes of tabular, vein-like form are included in group 4. In many districts which contain lodes characteristic of class 1, Miocene (?) dikes are abundant and in a number of places, such as the Lost Packer Mine, Loon Creek District, persistence of the

[11] Anderson, A. L., "Geology and Ore Deposits of the Lava Creek District, Idaho," Idaho Bur. of Mines and Geology Pamphlet No. 32, Aug., 1929.

crustal weakness that permitted the formation of Mesozoic lodes has tended to localize Miocene (?) dikes in and near these old lodes. To demonstrate that a given lode belongs in class 2, group 4, it is necessary to show that it was formed later than the intrusion of Miocene (?) dikes. This distinction has some economic bearing, since many of the lodes of this group are, like the Mesozoic lodes, within the borders of the Idaho batholith; but, as they were deposited at some distance from their source, they may be expected to contain more persistent ore shoots than the roots of Mesozoic lodes. On the other hand, with few exceptions, base-metal lodes of Tertiary age in this region have not yet proved of economic value and those lodes in group 4 in which lead and zinc are the principal assets will be regarded unfavorably by many. Most of the developed lodes in subgroup 1 are in the Boise Basin and have been worked largely for their precious metals. Ballard [12] and previous investigators have shown that some of the lodes here do belong to this subgroup, but it is possible that Mesozoic mineralization also exists in this famous district and present information is not sufficient to permit satisfactory distinction between the two.

Subgroup 2 in group 4 is represented by the quicksilver deposits of the Yellow Pine District. These are tentatively placed here largely because it appears improbable that quicksilver deposits of Mesozoic age would be formed so close to the main Idaho batholith. Genetic relation to Tertiary dikes or other igneous rocks has not been definitely shown, although both dikes and lava of Miocene (?) age are present in the vicinity.

Distribution of the Lodes of Class 2.—Accessible mines in lodes of class 2 are comparatively so scarce and shallow that no speculation as to zonal distribution is warranted; however, there are significant geologic factors controlling the distribution of the deposits. All the lodes, with the exception of those in the first subgroups in groups 3 and 4, lie in a zone of de-

[12] Ballard, S. M., "Geology and Gold Resources of Boise Basin, Boise County, Idaho," Idaho Bur. of Mines and Geology, Bull. 9, Dec., 1924.

formation and intrusion that extends southwestward from near Forney, Lemhi County, to the famous Silver City District, Owyhee County. The zone includes the upper valley of the Middle Fork of the Salmon River and the country on either side of it, continues across the Idaho batholith in southern Valley County, where it is represented by lines of weakness but no recognized lodes, and through the Boise Basin. The Lava Creek District (group 1, subgroup 2) and probably also the Alder Creek District (group 3, subgroup 1) lie in a less well-defined zone of northwesterly trend. The first zone includes the widespread broken upwarp of Miocene (?) volcanics with the largest known mass of Miocene (?) granite elongated along its axis, and southwest of the area of volcanics is marked by faults and lines of weakness reflected in the topography. The flexure, fractures, and granite mass have an average trend of about N. 45° E. There is a subordinate set of fractures, locally dominant, which trends about N. 40° W. This set evidently influenced the localization of the Lava Creek and Alder Creek lodes.

GENERAL ECONOMIC FEATURES.

The above outline shows that there are, on a genetic basis, two broad classes of lodes in south-central Idaho, of Mesozoic and Tertiary age respectively. The deposits of past and present economic importance in the first class are in shear zones (group 1) and are characterized by galena and other sulphides in a sideritic gangue. They have in the past yielded moderately rich ore from shoots of good size, but attempts to follow the lodes to any considerable depth have generally been unsuccessful. Hopes for the future, in these lodes, lie largely in solving the problems of finding new ore shoots at greater depth and of the metallurgical treatment of the more complex ore left by early operators. Although a few of the lodes belonging to other groups in this class are now profitable and others may become so as transportation develops, it appears that most of them can be profitably worked only on a small scale, if at all. Some of the large, low-grade bodies of gold ore,

now uncommercial, may eventually become important reserves.

The lodes of the second class have been and are likely to continue to be valuable mainly for precious metals, although a few good mines of copper and other base metals have been and will be developed. In the past the precious metal lodes have yielded rich ore, which, with a few notable exceptions, has been in rather small bodies. Such ore is becoming increasingly hard to find and the hope for the future, therefore, lies in the economic value of the large, low-grade bodies of gold ore which it is impractical to mine under present conditions, partly because of geographic position and partly because in many of them the fine state of subdivision of the precious metals, whether free or in selenide, presents difficult metallurgical problems.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

INTERGROWTHS OF BORNITE AND CHALCOPYRITE.[1]

G. M. SCHWARTZ.

INTRODUCTION.

In recent experimental work on intergrowths of chalcopyrite and cubanite,[2] as well as of bornite and chalcocite,[3] attention was drawn to the relations of bornite and chalcopyrite. These minerals exhibited relationships which were not easily explained and additional experiments were planned to attempt to clear up some of the points involved. The existence of intergrowths of these minerals, particularly of a reticulate or lattice type, has long been known and variously interpreted as noted below.

There is no doubt whatever that certain intergrowths of chalcopyrite in bornite result from replacement of bornite along crystallographic directions, but it also seems clear that some form in other ways. The question is, therefore, if some intergrowths are of one origin and some another, what characteristics distinguish them? The answer can not be complete until we understand, to some extent at least, how these intergrowths may form as primary structures. The experiments here reported show how some types of textures involving these minerals may form by the unmixing of solid solutions.

REVIEW OF LITERATURE.

Intergrowths of chalcopyrite and bornite are relatively common and were described in some of the earliest papers on the microscopic character of copper ores, as viewed in reflected light.

[1] The work on which this paper is based was aided by a grant from the research funds of the Graduate School of the University of Minnesota.

[2] Schwartz, G. M., "Intergrowths of Chalcopyrite and Cubanite," ECON. GEOL., vol. 22, pp. 44–61, 1927.

[3] Schwartz, G. M., "Experiments Bearing on Bornite-Chalcocite Intergrowths," ECON. GEOL., vol. 23, pp. 381–397, 1928.

Graton and Murdoch [4] describe chalcopyrite along the cleavage of bornite as a result of alteration; graphic intergrowths of the same minerals are also described.

In 1914 Kraus and Goldsberry published an elaborate paper [5] on the composition of bornite and concluded that bornite is variable and represents several sulpho-salts in the progression from Fe_2S_3 to Cu_2S.

Rogers [6] discussed Kraus and Goldsberry's results and interpreted them to mean not a series of compounds, but that bornite was a solid solution of Cu_2S in Cu_3FeS_3. Wherry [7] suggested that the variation might be explained by the existence of submicroscopic inclusions.

Whitehead [8] described reticulate intergrowths of chalcopyrite in bornite and explained them as due to replacements of bornite along crystallographic directions.

Overbeck [9] was perhaps the first to describe an intergrowth of bornite and chalcopyrite characteristic of a type now known to result by the unmixing of a solid solution. He assigned this intergrowth to an origin by replacement, although he noted that the gash-like replacement bands became narrow where two bands cross, instead of broadening out as would be expected if they were formed by replacement.

Tolman [10] described and figured several samples of intergrowths of chalcopyrite in bornite. Figure 20 contains, according to Tolman, two generations of chalcopyrite. It is possible that one of the generations may be due to unmixing. Tolman and

[4] Graton, L. C., and Murdoch, J., "The Sulphide Ores of Copper," *Trans. A. I. M. E.*, vol. 45, pp. 26–73, 1913.

[5] Kraus, E. H., and Goldsberry, J. P., "The Chemical Composition of Bornite and its Relation to Other Sulpho-minerals," *Amer. Jour. Sci.*, vol. 33, pp. 539–553, 1914.

[6] Rogers, A. F., "The Chemical Composition of Bornite," *Science*, vol. 42, pp. 386–388, 1915.

[7] Wherry, E. T., Discussion: *Science*, vol. 42, pp. 570–571, 1915.

[8] Whitehead, W. L., "Paragenesis of Certain Sulphide Intergrowths," ECON. GEOL., vol. 11, pp. 1–13, 1916.

[9] Overbeck, R. M., "Copper Ores of Maryland," ECON GEOL., vol. 11, pp. 151–178, 1916.

[10] Tolman, C. F., "Observations on Certain Types of Chalcocite and their Characteristic Etch Patterns," *Trans. A. I. M. E.*, vol. 54, pp. 401–433, 1916.

Rogers [11] figured a specimen from Engels, California, with bornite altering to covellite and chalcopyrite. It is noteworthy that the chalcopyrite blades are absent from the margin of the bornite where one would expect them to be abundant if formed by replacement.

Graton and McLaughlin,[12] however, show an example of bornite and chalcopyrite with chalcocite which seems clearly to have been due to replacement, probably supergene.

McLaughlin [13] has also described chalcopyrite replacing bornite along the cleavage in specimens from the Evergreen mine.

Examples of the lattice texture are described from the Kennecott mine.[14] Some seem clearly replacement, others from the descriptions suggest the possibility of an explanation by unmixing.

Uglow [15] has described and discussed in some detail a bornite-chalcopyrite intergrowth from Legate Creek, Pacific, B. C. He notes that at magnifications of 100 the bornite appears homogeneous, but higher magnifications show a maze of minute needles of chalcopyrite. The inclusions were interpreted as replacement and not primary intergrowths, and five lines of evidence were given to substantiate the interpretation. Uglow's textures are duplicated in the experiments described below by what is clearly unmixing of a solid solution.

Schneiderhöhn [16] discussed chalcopyrite and bornite intergrowths in his paper on unmixing textures and cited an example found in a specimen from a furnace at the Tsumeb mine, South Africa.

[11] Tolman, C. F., and Rogers, A. F., "A Study of Magmatic Sulfid Ores," Leland Stanford Junior Publications, 1916.

[12] Graton, L. C., and McLaughlin, D. H., "Ore Deposition and Enrichment at Engels, California," ECON. GEOL., vol. 12, pp. 1–27, 1917.

[13] McLaughlin, D. H., "Ore Deposition and Enrichment at the Evergreen Mine, Gilpin County, Colorado," ECON. GEOL., vol. 14, pp. 465–479, 1919.

[14] Bateman, A. M., and McLaughlin, D. H., "Geology and Ore Deposits of Kennecott, Alaska," ECON. GEOL., vol. 15, pp. 1–31, 1920.

[15] Uglow, W. L., "A So-called Bornite-Chalcopyrite Intergrowth," *Amer. Min.*, vol. 7, pp. 1–4, 1922.

[16] Schneiderhöhn, H., "Entmischungserscheinungen innerhalb von Erzmischkristallen," *Metall und Erz*, vol. 19, pp. 501–508 and 517–526, 1922.

Geijer [17] has given the best natural example of a probable unmixing texture of chalcopyrite and bornite, and has discussed its origin with the conclusion that it did result from unmixing. This conclusion is strongly supported by a comparison of photographs of a typical segregate of a nickel-silicum alloy with the bornite-chalcopyrite intergrowth.

Excellent examples of chalcopyrite along the cleavage of bornite but related to veins and cracks, are known from Butte.[18]

Guild [19] has described crystals of bornite from a dismantled copper furnace. Intergrowths of chalcopyrite were found in the crystals.

Van der Veen [20] gives an example of chalcopyrite lattice texture in bornite and explains it as due to segregation from a solid solution. He also shows the replacement of bornite by chalcopyrite forming a lattice texture. An excellent example of a graphic intergrowth of bornite and chalcopyrite is also shown and interpreted as a eutectoid texture, but without citing the reasons for considering it of that origin.

Short and Ettlinger [21] describe chalcopyrite as veinlets and plates cutting bornite; the chalcopyrite was considered supergene. They note that these gratings have been produced artificially by immersing bornite in dilute sulphuric acid, by immersion in a 5 per cent. solution of cupric sulphate, by action of heated sulphur vapor on bornite, and by unmixing of a bornite solid solution.

EXPERIMENTAL DATA.

The methods employed were essentially those described in previous papers by the writer.[22] Small specimens containing, in

[17] Geijer, P., "Some Swedish Occurrences of Bornite and Chalcocite," Sver. Geol. Undersökning, Ser. C, No. 321, 1924.

[18] Locke, A., Hall, D. A., and Short, M. N., "Rôle of Secondary Enrichment in Genesis of Butte Chalcocite," *Trans. A. I. M. E.*, vol. 70, pp. 933–963, 1924.

[19] Guild, F. N., "Bornite as a Furnace Product," *Amer. Min.*, vol. 9, pp. 201–205, 1924.

[20] Van der Veen, R. W., "Mineragraphy and Ore Deposition," Hague, 1925.

[21] Short, M. N., and Ettlinger, I. A., "Ore Deposition and Enrichment at the Magma Mine, Superior, Arizona," *Trans. A. I. M. E.*, vol. 74, pp. 174–222, 1926.

[22] *Op. cit.*

so far as practicable, only bornite and chalcopyrite, were polished and examined under the microscope. Part of the original specimen was always retained for comparison. The pieces selected were sealed in pyrex tubes for temperatures up to 650° C. and in silica tubes for temperatures above 650° C. The sealed tubes were heated in a small alundum core resistance furnace wound with nichrome wire which operated on a 110 volt alternating current. Temperatures were measured with a chromel-alumel thermo-couple attached to a Leeds and Northrup potentiometer. An air quench was tried because of the gas pressure in the tube, but this did not cool the specimens quickly enough. An electric fan was also tried with outside air below freezing, but this too was unsuccessful. A water quench was successful, but caution should be used as rather violent explosions sometimes result and the operator should be protected from flying glass.

The desired temperatures could not be strictly maintained due to fluctuations in the voltage of the line and variations of as much as 10 or 15 degrees from the stated temperature were caused by the fluctuations during the night. The resistance was set to hold the temperature at or below the desired figure. The small variation was of no consequence in most of the experiments, but in determining the lower limit of solution care was taken not to exceed the stated temperature. Repetition of some of the experiments with accurate control will eventually be necessary.

After cooling, the specimens were repolished, or if broken up by heating they were mounted in sealing wax and polished in the usual manner.

Various natural specimens were used in the experiments, the choice being usually made because the particular specimens showed relatively pure bornite and chalcopyrite more or less intimately mixed, but not showing crystallographic intergrowths. Specimens from several regions were used to eliminate possibility of error due to unusual material.

The first experiment consisted in heating a specimen at 500° C. for 25 hours and then cooling as quickly as possible in air. Excellent intergrowths were found in both the former bornite

TABLE I.

TABULATION OF EXPERIMENTS.

No.	Source of Specimen	Minerals in Original Specimen. Predominant Mineral First	Temperature	Time	Quench or Time of Cooling
1	Globe	Bornite-chalcopyrite	500° C.	20 hrs.	Water quench
2	"	" "	500° C.	48 "	Air quench
3	"	" "	500° C.	72 "	" "
4	"	Bornite	600° C.	72 "	" "
5	"	Bornite-chalcopyrite	500° C.	69 "	" "
6	"	Bornite	650° C.	18 "	Cooled in furnace
7	"	"	550° C.	96 "	" " " $2\frac{1}{2}$ hrs.
8	Parry Sd., Ontario	"	550° C.	96 "	Air quench
9	Engels, Cal.	"	550° C.	96 "	Cooled in furnace $2\frac{1}{2}$ hrs.
10	Susie Is.	Chalcopyrite-bornite	550°–600°C.	72 "	Air quench
11	" "	" "	600° C.	46 "	" "
12	" "	Part Exp. 11 returned	600° C.		Slow cool; 21 hrs.
13	" "	Chalcopyrite-bornite	600° C.	7 days	Air quench
14	Globe	Bornite	600° C.	7 "	" "
15	"	Bornite-chalcopyrite	600° C.	7 "	" "
16	Susie Is.	Chalcopyrite-bornite	600° C.	6 "	" "
17	Globe	Bornite (crushed)	600° C.	6 "	" "
18	"	" (40 mesh)	650° C. ±	44 hrs.	Cooled in furnace
19	"	" (60 mesh)	650° C. +	24 "	" " "
20	Bisbee	Bornite-chalcopyrite	700° C.	44 "	Air quench
21	"	" "	700° C.	41 "	" "
22	"	" "	600° C.	48 "	" "
23	"	Part Exp. 21 returned	625° C.		Slow cool; 26 hours
24	"	Part Exp. 21 returned	700° C.	65 "	Air quench
25	"	Part Exp. 20 returned	650° C.		Reheat and slow cool; 24 hours
26	Globe	Bornite-chalcopyrite	800° C.	46 "	Air quench
27	"	" "	600° C.	48 "	Water quench
28	"	Part Exp. 27 returned	600° C.		Cooled in 1 hour
29	"	Part Exp. 27 returned	600° C.		" " 5 minutes
30	Engels, Cal.	Bornite-chalcopyrite	400° C.	72 hrs.	Air quench
31	Bisbee	" "	400° C.	7 days	" " no effect
32	"	" "	450° C.	7 "	" " no effect
33	"	Chalcopyrite-bornite	600° C.	48 hrs.	Slow cool; 6 hours
34	"	Bornite-chalcopyrite	475° C.	6 days	" " 2 hours
35	"	Chalcopyrite-bornite	600° C.	47 hrs.	Air quench
36	Globe	Bornite	650° C. +	48 "	Cooled in furnace
37	Bisbee	Bornite-chalcopyrite	475° C.	7 days	Air quench
38	Globe	Bornite	600° C. +	4 "	Cooled in furnace
39	Bisbee	Part Exp. 35 returned	600° C.		Slow cool; 20 hours

and chalcopyrite areas. The structures were of the types shown in Figs. 1 and 2. The coarseness of these intergrowths compared to those produced in previous experiments on chalcopyrite-cubanite, and bornite-chalcopyrite, was obvious and rather puzzling and unexpected. Some of the intergrowths may be easily observed at magnifications of 75 diameters. Repetitions of this experiment were made increasing both the time and temperature in an attempt to produce a solid solution, but the results were always the same until a quench in water was made from 600° C. (Exp. 27.) In this specimen the solid solution was retained. Part of the material from this experiment, when returned and cooled in air from 600° C. (Exp. 29), showed excellent intergrowths of the type commonly found in previous experiments.

Some of the solid solution was also reheated and cooled in one hour (Exp. 28), with a texture shown in Fig. 5 resulting. The larger size of the blades of chalcopyrite is evident compared with those in specimens withdrawn from the furnace and cooled in air. There is also a pronounced tendency of chalcopyrite to segregate to the grain boundaries. Van der Veen [23] has noted the tendency of pentlandite to segregate to the grain boundaries in the Sudbury ores and attributes it to the breakdown of a solid solution during very slow cooling. The writer found the same relation of ilmenite to magnetite in the Duluth gabbro.[24] Van der Veen's conclusions regarding the origin of this texture seem strikingly confirmed by these experiments.

Parts of specimens from other experiments were cooled from 600° C. to room temperature in 24 hours with the result that the intergrowths became very coarse or disappeared altogether and the chalcopyrite segregated into grains in the predominant bornite as shown in Fig. 6. The complete segregation of the minor constituent into grains is most surprising and brings out a fact which has been very little considered in geologic theory; that is, that even more or less granular mixtures of two constituents may represent a breakdown of a solid solution that existed at higher temperatures.

[23] Van der Veen, "Mineragraphy and Ore Deposition," Fig. 15, The Hague, 1925.

[24] Schwartz, G. M., "The Relations of Magnetite and Ilmenite in the Magnetite Deposits of the Duluth Gabbro," *Amer. Min.*, vol. 15, pp. 243–252, 1930.

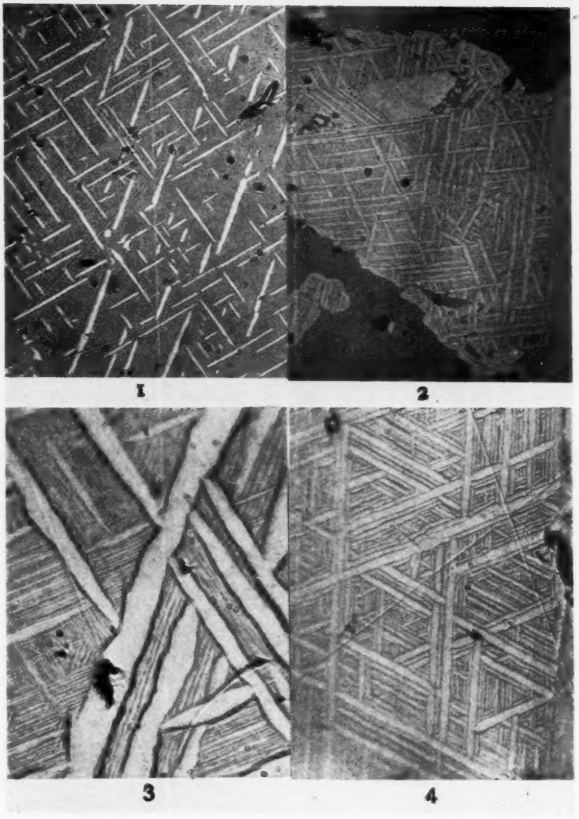

FIG. 1. Specimen of bornite and chalcopyrite from Globe, Arizona, heated at 500° C. for 72 hours. Bornite areas were entirely free from chalcopyrite previous to heating. Several variations of this texture were obtained. It is characteristic of predominant bornite and is identical with some natural textures. × 190.

FIG. 2. Area of same specimen as Fig. 1, which was apparently pure chalcopyrite previous to heating. Now a lattice intergrowth of chalcopyrite (white) and bornite (dark) characteristic of predominant chalcopyrite. Not known in natural specimens. × 166.

FIG. 3. Enlargement of small area of Fig. 2. Note particularly that the chalcopyrite blades contract at intersections instead of enlarging as in replacement textures. × 585.

FIG. 4. Chalcopyrite-bornite specimen from Bisbee, Arizona, heated 48 hours at 600° C. Triangular intergrowth of an area formerly chalcopyrite. Figures 3 and 4 are characteristic of predominant chalcopyrite specimens at high magnifications. × 750.

In determining the minimum temperatures at which the solid solution of bornite and chalcopyrite would form, several experiments were run for a duration of a week each. The temperatures tried were 400° C., 450° C., 475° C., and 500° C. No definite effects could be determined at either 400° C., or 450° C., but at 500° C. the solid solution was abundantly formed in a week, and on cooling the usual intergrowth resulted. At 475° C. the effect of heating was beyond doubt, although diffusion was far from complete in seven days. The minimum temperature at which the solid solution forms is therefore about 475° C. and it is at about this temperature that unmixing occurs. Conditions in nature may of course modify the transformation temperatures and this must be considered in applying the results to ore deposits.

The texture resulting from the breakdown of a solid solution of bornite and chalcopyrite depends on which mineral is in excess, as is clearly shown by Figs. 1 to 6. The rate of cooling is also a most important factor. Specimens high in bornite show the textures of Figs. 1, 5 and 6, each type representing a different rate of cooling. Specimens with an excess of chalcopyrite show the textures of Figs. 2 to 4, with variations.

The rate at which bornite will segregate out of chalcopyrite seems to be very much slower than that at which chalcopyrite segregates from bornite. Specimens with predominant chalcopyrite which have cooled in 24 hours show a stage of segregation about equal to that of predominant bornite cooled in one hour.

The textures illustrated in Figs. 1 to 6 are the types produced most commonly, but variations were occasionally found; for example, experiment 33 showed some areas of chalcopyrite with spindle-shaped bornite inclusions oriented along crystallographic directions. Within the same specimen other areas of predominant chalcopyrite contained the usual texture.

It was also observed that predominant chalcopyrite areas included in bornite in some specimens show a narrow border of chalcopyrite free from bornite. (Fig. 2 shows this to a slight extent.) This may be due to the bornite escaping from the chalcopyrite near the edge.

Of the artificial textures observed, only that of Fig. 1 is known in a natural form in so far as the writer is aware.

In specimens with fairly large areas of chalcopyrite in bornite, heated not much above the temperature of solution, only the borders of the chalcopyrite areas show intergrowths. Continued heating at higher temperatures results in diffusion affecting the

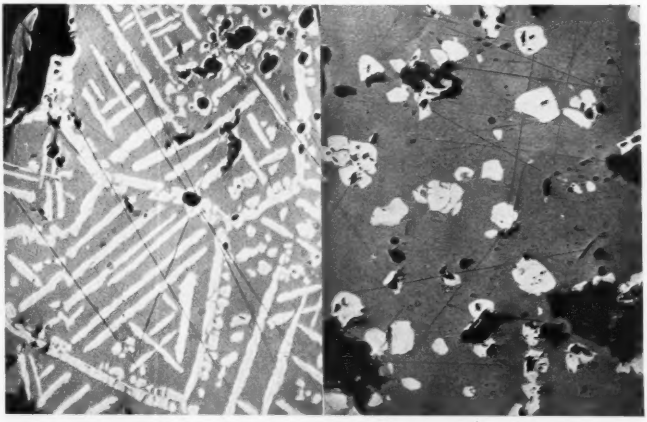

FIG. 5. Chalcopyrite-bornite specimen from Bisbee, Arizona, heated 41 hours at 700° C. Cooled in air. Note segregation of chalcopyrite to grain boundaries of the bornite. This was observed only in predominant bornite specimens. × 100.

FIG. 6. Bornite-chalcopyrite specimen from Bisbee. Heated 48 hours. at 600° C. and cooled in air. This showed texture like Fig. 5. Specimen reheated to 600° C. and cooled slowly for 24 hours. The chalcopyrite has segregated in grains or crystals in the bornite. × 50.

entire specimen. This brings out clearly the general process of formation of the solid solution by diffusion and the importance of the time element. The two minerals gradually diffuse into each other and presumably over a long period of time would become homogeneous. In fact specimens consisting originally of fairly fine-grained mixtures heated at 600° C. or higher, become essentially uniform in even the limited time used in these experiments.

In most of the experiments with high bornite specimens heated at 500° C. or higher, there was rather complete decrepitation of the polished specimens in the tube, making it necessary to mount the fragments in sealing wax for repolishing. This decrepitation seemed to occur at about the temperature at which the solid solution formed and suggests a rather decided volume change, possibly due to an inversion in crystal structure. This decrepitation did not take place in the series of experiments with chalcopyrite and cubanite [25] over a similar range of temperature, from which it is inferred that bornite is responsible. Several experiments were ruined by explosions violent enough to break extra thick-walled pyrex tubes. This was presumably due to sudden and unusually violent decrepitation of the specimens.

DISCUSSION.

The experiments here reported seem to prove that chalcopyrite and bornite dissolve in each other to form a solid solution. Unless the solid solution is drastically quenched, however, it breaks down and segregates with amazing rapidity into a crystallographic intergrowth of the subordinate mineral in the predominant one. A cooling time of five minutes from 600° C. to room temperature allows sufficient segregation so that the intergrowth may be observed at a magnification of 75 diameters (Fig. 1). Cooling in one hour allows segregation of some of the subordinate mineral to grain boundaries (Fig. 5), and 24 hours in some cases results in complete segregation into grains (Fig. 6). This extremely rapid segregation is remarkable and clearly explains why ores showing good intergrowths of chalcopyrite in bornite formed by ex-solution are rare in nature. Intergrowths of a similar type resulting from replacement are common, as is shown by a review of the literature. Of the papers reviewed above, only those by Overbeck, Tolman, Tolman and Rogers, Geijer and probably Uglow, describe natural textures which seem best explained as a result of unmixing. Schneiderhöhn and Guild have described

[25] Schwartz, G. M., "Intergrowths of Chalcopyrite and Cubanite," ECON. GEOL., vol. 22, pp. 44–61, 1927.

furnace products showing the texture. The writer does not recall having seen a natural specimen of unmixing of chalcopyrite-bornite among hundreds of specimens containing these minerals. In fact it is surprising that there are any examples in nature, where cooling is, as a rule, very slow. The scarcity of natural bornite-chalcopyrite intergrowths contrasts with minerals like chalcopyrite-cubanite, which show the crystallographic intergrowth in practically all of the deposits that have been described.

There is another reason for the relative scarcity of examples of unmixing of chalcopyrite and bornite. The minimum temperature at which these minerals seem to dissolve is about 475° C. Since bornite and chalcopyrite occur most abundantly in deposits of the moderate depth type (mesothermal) they probably are deposited above this temperature only rarely. The presence of such an intergrowth as that described and figured by Geijer [26] would strongly suggest deposition above 475° C. with rapid cooling. It is noteworthy in this connection that several examples of probably magmatic bornite are described in the literature. These are summarized in Clarke's Data of Geochemistry.

It is evident from the differences in texture developed by specimens predominant in bornite and those predominant in chalcopyrite that there are distinct differences in the controlling conditions at the two ends of a binary system containing bornite and chalcopyrite. Evidently the crystal structure of the predominant mineral controls the type of crystallographic intergrowth as would be expected. In other words, when bornite is predominant chalcopyrite dissolves in it at temperatures above 475° C. and on cooling the chalcopyrite is found to take up a position along certain crystallographic planes in the bornite. The reverse is true when chalcopyrite predominates. It is also apparent that chalcopyrite segregates out of bornite more rapidly than bornite out of chalcopyrite. No segregation to grain boundaries or formation of grains was noted in predominant chalcopyrite specimens cooled the same length of time as the specimens from which Figs. 5 and 6 were photographed. Probably the temperature at which the solid

[26] *Op. cit.*, Fig. 15.

solution forms is somewhat higher at the chalcopyrite end of the system.

FORMATION OF CRYSTALS.

In some of the first experiments it was found that specimens heated at 500° C. or higher for 24 hours and longer show minute but well developed crystals over part of the surface, including the polished face. Repetition of the experiments at higher temperatures and longer time resulted in the development of more and somewhat larger crystals and it seemed that they were more abundant in specimens that decrepitated during the heat treatment. With this in mind, bornite and mixed bornite-chalcopyrite specimens were crushed to pass 60 mesh and subjected to the same treatment. This resulted in an even more conspicuous development of crystals.

The crystals were usually the color of the bornite, although in a few cases they were evidently chalcopyrite. On the faces of the bornite crystals, oriented blades of chalcopyrite were observed, and their presence in Experiment 26 was proved by picking out several crystals under a binocular and polishing them mounted in sealing wax. They showed much intergrown chalcopyrite.

On polished specimens that did not decrepitate, the crystals are commonly most abundant around one end; presumably this was the cooler end. Examination with a binocular permitted rather close observation of the relation of the crystals to the original specimen. They are clearly formed on and extend above the polished surface. In some cases several crystals grow one above the other, forming a small wire-like projection. The polished surface is further broken by numerous pits or craters obviously representing the source of some of the material constituting the crystals.

Unfortunately none of the perfect crystals are large enough to measure with a goniometer. The largest observed has a diameter of 1.7 mm. The crystals are commonly twinned, but the simple forms seem to be isometric, with cubes and octahedrons the most common combination. In some specimens tetrahedrons seem to

be the abundant simple form, in others possibly pyritohedrons. In several specimens, the faces are composed of oscillatory growths and the forms are not recognizable. Several experiments were made with bornite crushed to pass 60 mesh and, as expected, the formation of crystals was increased. When heated to 600° C., this material seemed to cement itself somewhat, partly by incipient fusion and partly by recrystallization. It was also observed in these experiments, as in others with polished specimens, that the crystals develop mainly at one end, presumably the end which may have been slightly cooler, due to its location slightly off from the center of the furnace. It seems evident that these crystals had formed by volatilization as evidenced by their deposition on the polished surfaces and the presence of craters elsewhere on the surfaces.

Evidence of recrystallization is obvious on specimens from most of the experiments. Bornite especially seems to develop a polysynthetic twinning, evidently octahedral, as triangular-shaped cleavage faces are commonly conspicuous. Perfect cleavage of the type developed has not been observed in bornite, but a similar texture has been described by the writer in chalcopyrite from Parry Sound.[27] The artificial structure seems more conspicuous in bornite than in chalcopyrite.

The suggestion that bornite crystals may form by volatilization is not new, as it was noted in 1901 by A. N. Winchell [28] that bornite and chalcopyrite formed by sublimation in a smelter at Butte. Guild[29] has also described crystals formed in a furnace, as has Schneiderhöhn.[30] The rather low temperature at which the crystals formed in the experiments reported above is rather surprising. Further work along this line extending it to other sulphides might yield suggestive results.

[27] Schwartz, G. M., "Primary Relationship and Unusual Chalcopyrite in Copper Deposits at Parry Sound, Ontario," ECON. GEOL., vol. 19, pp. 209–213, 1924.

[28] Winchell, A. N., "Note on Certain Copper Minerals," *Amer. Geologist*, vol. 28, pp. 244–246, 1901.

[29] *Op. cit.*

[30] *Op. cit.*

CONCLUSIONS.

1. Mixtures of bornite and chalcopyrite heated above 475° C. form a solid solution which may be retained at room temperature by quenching in cold water.

2. Solid solutions of bornite and chalcopyrite cooled in five minutes show diagrammatic crystallographic intergrowths as a result of the unmixing of the solid solution.

3. Solid solutions of predominant bornite and subordinate chalcopyrite when cooled slowly show segregation of chalcopyrite to the boundaries of the bornite grains. If the cooling time is 24 hours or more the chalcopyrite may segregate into grains.

4. There is a distinct difference in the type of intergrowth, depending on which mineral predominates (Figs. 1 to 4).

5. From the temperature at which the solid solution forms on heating, and unmixes on cooling, it is inferred that deposits showing intergrowths of chalcopyrite in bornite (not replacements) were formed at or above 475° C.

6. The high temperature of formation of the solid solution suggests an explanation for the comparative scarcity of these intergrowths in nature, since most sulphide deposits are probably formed below 475° C., especially those in which bornite is found abundantly.

7. The scarcity of intergrowths of the types described may also be explained by the rapidity with which segregation takes place when the solid solution unmixes.

8. The fact that granular aggregates of two ore minerals may result from unmixing of a solid solution has not been previously demonstrated to the writer's knowledge.

9. Bornite and chalcopyrite crystals may be formed artificially by sublimation at temperatures as low as 500° C.

ACKNOWLEDGMENTS.

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VLAKFONTEIN NICKEL DEPOSITS, RUSTENBURG AREA, TRANSVAAL, SOUTH AFRICA.

ROBERT D. HOFFMAN.

INTRODUCTION.

THE following paper is based upon an examination, in the summer of 1929, of the nickel properties of the South African Mineral Company, Ltd., situated in the Pilandsberg area, Bushveld, thirty-eight miles northwest of the town of Rustenburg, Transvaal, South Africa. During the underground examination in July, the writer was materially assisted by Dr. J. Graham Mitchell of Johannesburg, whose help he here gratefully acknowledges. The course of the work was much facilitated by the reports and maps compiled by Mr. E. R. Schoch, who has been the consulting engineer for the above-named company since 1926. In addition to such assistance, the writer was materially benefited by the advice and counsel of Colonel R. Weekes, superintendent of the company.

Dr. P. A. Wagner has very fully and ably described the mineralogy and petrography of the deposits and the reader is referred to his memoir "Magmatic Nickel Deposits of the Bushveld Complex in the Rustenburg District, Transvaal," [1] for these details. Since the completion of his excellent report in 1924, however, more underground work, giving additional facilities for making more complete observations, has revealed conditions which throw new light on the origin of these deposits.

Mr. E. R. Schoch [2] in a very interesting paper described these deposits and pointed out that the theory of origin of "magmatic segregation" advanced by Dr. Wagner was un-

[1] Wagner, Percy A., Memoir 21, Dept. Mines, Pretoria, Transvaal, Union of South Africa.

[2] *Chem. Met. Min. Soc. South Africa*, pp. 150–157, Johannesburg, January, 1929.

tenable. Schoch, who was the first to question this theory, suggested that pneumatolysis was a more likely explanation of ore genesis and that the Pilandsberg intrusive may have had some genetic connection with the nickel deposit.

The writer fully agrees with Mr. Schoch that the "magmatic segregation *in situ*" theory advanced by Dr. Wagner is untenable as revealed by underground conditions. The plan of this paper is to sketch briefly the general geology and the local mine geology, then indicate in detail the underground structural relationships of the nickel deposits and, finally, discuss the origin. The writer is not including any detailed descriptions of the mineralogy and petrography of the deposits, since he feels such descriptions here are incidental to the comprehension of the genesis of the deposits and that the structural relationships of the ore deposits to the adjacent rocks, and of the adjacent rocks to the general geology of the area, are far more significant.

SUMMARY.

The nickel deposits of Vlakfontein were formed after the harzburgite had fully differentiated out in the bronzitite and both rocks had crystallized. The pipe-like ore bodies, vertical in character, show typical replacement structure and are equally developed in both the harzburgite and bronzitite, cutting across and replacing these rocks, which are here dipping at a low angle. The ore structure is at right angles to the rock structure. There is no field evidence to support the theory of "magmatic segregation *in situ*." There may have been magmatic segregation in depth. The ore bodies were formed by agencies that came from below, after the host rocks had been intruded into the overlying sediments and crystallized. The writer prefers not to express any opinion as to whether these deposits were formed by hydrothermal solutions or were injected as molten sulphides, believing that this question can best be answered by geochemists. The nature of the ore and the lack of characteristic pneumatolytic minerals seem to rule out the pneumatolysis theory suggested by Mr. Schoch.

HISTORY.[3]

The earliest development of the deposits began in 1910, at which time work on some gossans revealed pyrrhotite ore, carrying nickel, at a depth of 40 feet. Since that date, development work was conducted more or less intermittently until 1925, when the South African Mineral Company, Ltd., was formed. This company proceeded to investigate and explore the deposits systematically, finally ceasing active work in August, 1928. Since that time, however, the underground workings have been kept free of water, pending further exploration.

GENERAL GEOLOGY.

The general geology of the area, a part of the Bushveld Complex, is shown in Fig. 1.

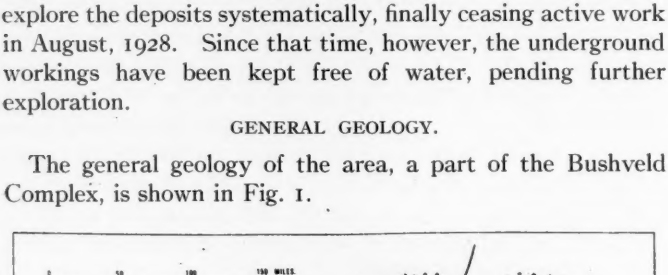

FIG. 1. Geological sketch map showing position of nickel deposits and of western margin of main portion of the Bushveld Basin. (Taken from Wagner's Report, "Magmatic Nickel Deposits of Bushveld Complex, Rustenburg District, Transvaal," Mem. 21, Dept. of Mines, Geol. Surv. Union of So. Africa.) *OG*, Old granite; *BR*, Black reef; *D*, Dolomite; *Pr*, Pretoria Series; *W*, Waterberg System; *N*, Norite; *BG*, Bushveld granite; ●, Nepheline rocks (*P*, Pilandsberg Complex); *K*, Karroo System; *KA*, Bushveld amygdaloid; — *Ni*, Nickel deposits; — - —, Western margin of main portion of Bushveld Basin.

[3] For a detailed history of the deposits, the reader is referred to the prospectus of South African Minerals, Ltd., issued in 1925, and to the first annual report of the company for year ending September 30, 1926.

The norite in the Pilandsberg area is exposed on the surface more or less continuously for a width of 26 to 30 miles. The occurrence of residual quartzite erosion islands over this entire width, and the flat pseudo-bedding of the norite, 10° to 20°, suggest that the norite here dips at a very low angle.

The norite has undergone some differentiation, as indicated by development of harzburgite and anorthosite, but does not show the extreme acid differentiation of the Sudbury norite, which changes from a basic rock to an acid pegmatite in a horizontal distance of one-half to one mile. The greatest variation which the writer observed was that from diabase on farm Syferfontein 625 to a heavy olivine rock with chromite (harzburgite) on Vlakfontein 902, a distance of 7 miles. It is difficult to visualize a heavy rock like dunite outcropping on farm Groenfontein 302, some 5 miles from the contact, unless we assume a roll in the norite with the overlying mass removed by erosion. This suggests that the actual structure of the norite in the Pilandsberg area may be that of an intrusive sill with a number of "rolls," rather than that of an intrusive laccolith.

Local Mine Geology.—To return more specifically to the section surrounding the mine, the geology may be briefly described as follows: There is an area of bronzitite [4] (a special type of norite which shows a development of bronzite pyroxene) with lenses of very fine-grained basic differentiate, described by Wagner as harzburgite. According to Wagner, this harzburgite is made up of basic feldspar, bronzite, and olivine in a fine-grained ground mass with large phenocrysts of orthorhombic pyroxene. The harzburgite is a dark colored rock, almost black in appearance, whereas the bronzitite is a light colored rock varying from light to dark brown. On the surface the harzburgite alters readily to a fine-grained aggregate of serpentine.

Locally in the bronzitite there are small lenses of anorthosite from 2 to 50 feet long. These merely represent petro-

[4] The writer is using the terminology of Dr. Wagner in discussing the ore geology in order to avoid confusion in the reader's mind.

graphic curiosities and are not in a structural sense important. Intruding the harzburgite and the bronzitite are narrow fine-grained dikes that the writer has tentatively called diabase.

The harzburgite occurs in the form of flat canoe-shaped lenses in the bronzitite. These lenses vary from 100 to about 1000 feet in length and have a dip of from 10° to 30° to the northwest. Underground the bronzitite and harzburgite are seen to grade insensibly into each other and one cannot obtain a closer contact than a few inches, which represents the section where the bronzitite ends and the harzburgite begins. There are no selvages or any signs of intrusive contact between these two rocks and the harzburgite is clearly a differentiation product of the parent rock.

In the vicinity of the mine, Vlakfontein 902, the norite has evidently suffered very little erosion, as shown by the various outlyers of quartzite and slate in the main norite mass, residual islands, as it were, of the overlying roof of sediments into which the norite was intruded. To the south of, and parallel to, the main mass of norite, at varying distances up to 20 miles from it, are a number of "diabase" sills one quarter to one half mile wide, intrusive into the sediments of the Transvaal system.

ORE DEPOSITS.

The nickel-copper deposits occur in the main norite mass about 3½ miles north of the south contact with the sediments. The area is covered with overburden, outcrops are few, and it is difficult to determine the structure from the surface. As a rule, however, the overburden is rarely over 5 feet deep in the vicinity of the mine and trenching can be and has been advantageously employed.

The ore consists of pyrrhotite containing some pentlandite and chalcopyrite replacing the bronzitite (the name given locally to the norite) and the harzburgite, a basic differentiate of the norite. In the upper levels, immediately below the gossan, marcasite is an abundant constituent of the ores, but I am inclined to believe that the marcasite is largely secondary. Associated with the sulphides, at times, is chromite, particu-

larly in No. 1 ore body on the 300-foot level. Graphite also is present in the ore. A very small amount of pyrite and siderite is present as tiny veinlets cutting the ore.

Along with the introduction of the sulphides there has been some development of biotite and pyroxene as gangue, in the form of coarse tabular crystals, up to one inch in length.

The ore varies from (1) rock containing a small proportion of disseminated sulphides, 10 per cent. or less, to (2) heavily disseminated sulphides, and (3) massive sulphides. Roughly, I would estimate that in each one of the ore bodies examined, namely, Nos. 4, 1, 3, and 2, and the Rock Shaft ore body, there is a minimum of 25 per cent. included rock, less than half of the remainder being massive sulphides.

The ore bodies are approximately vertical in dip and pipe-like in character, and vary from a maximum of 70 feet to a minimum of a few feet in width. The largest cross section of ore developed on any one level in any ore body was 2450 square feet in No. 4 ore body at the 100-foot level. The ore bodies are quite scattered on the surface; No. 4 ore body is 700 feet from No. 1, 1000 feet from No. 2, 2000 feet from No. 3, and 1250 feet from No. 1*b* (Rock Shaft). Also, there is some mineralization several miles to the west, and a number of lenses lie scattered over a stretch of 17 miles to the north. The small lens, 50 feet in diameter, developed on farm Groenfontein 305, is approximately 17 miles north of No. 4 ore body. For the purpose of convenience, the writer will confine the discussion to Nos. 4, 3, 2, and 1*b* (Rock Shaft) ore bodies, which have had the most underground development.

There is apparently no structural feature to account for the position of the individual ore bodies, except some narrow diabase dikes, a few inches in width, which may have been intruded along pre-existing cracks and which served as channels, nor is there any structure visible on the surface to account for the relationship of the various lenses to one another. These lenses do not appear to be in any way affected by the character of the rocks surrounding them. In every instance the ore bodies were seen to have been formed

by replacement and later than the rocks in which they occur, with little difference in character whether they replaced bronzitite or harzburgite.

The relationship between the harzburgite and bronzitite and the ore bodies, which is clearly revealed by underground development, shows the harzburgite to occur in the bronzitite as flat-lying lenses, 10 to 100 feet wide, 10 to 200 feet thick. On the 100-foot level, Main Shaft area, the harzburgite is exposed at the shaft station, and the contact with the bronzi-

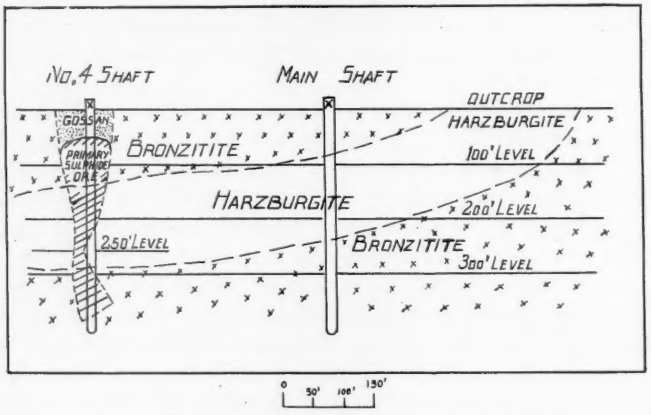

FIG. 2. Longitudinal section through No. 4 and Main Shafts, looking north.

tite is exposed for several hundred feet; the top of the lens dips below the floor of the drift before the No. 4 ore body is reached, which here is entirely in bronzitite. This is about 200 feet long. On the 200- and 250-foot levels, all the workings are in harzburgite and the ore body has replaced harzburgite. On the 300-foot level, the ore is in bronzitite. The harzburgite lens has thus a maximum thickness of 175 feet. Another lens of harzburgite is exposed on the 72-level crosscut and is a small canoe-shaped body, 30 feet in length; another is exposed in the southwest crosscut, west of No. 1 ore

body. The above relationships are clearly revealed in the longitudinal section (Fig. 2).

No. 4 ore body outcrops in bronzitite, and occurs in bronzitite on the 92-foot level, in harzburgite at the 200- and 250-foot levels, and in bronzitite on the 300-foot level. No. 4 shaft, sunk in the ore body, showed that this is a continuous vertical ore body cutting across the bronzitite and harzburgite.

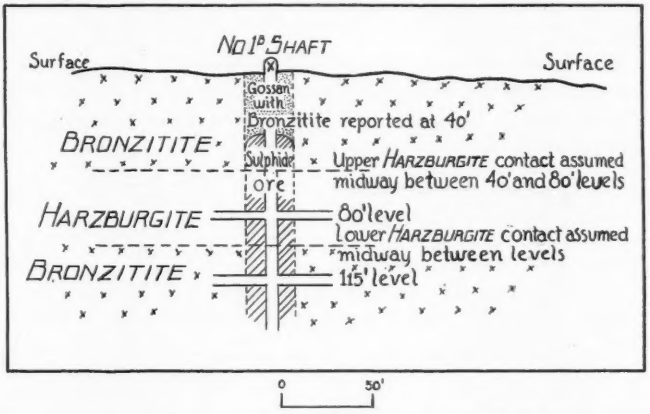

FIG. 3. East-west cross section through No. 1*b* Shaft, looking north.

Rock Shaft ore body, No. 1*b*, outcrops in bronzitite and occurs in harzburgite on the 80-foot level, and in bronzitite on the 115-foot level. Here again is clear-cut evidence that the sulphides were introduced after the rocks had differentiated in flat-lying layers and that the ore structure, vertical in character, is at right angles to the structure of the rocks.

No. 3 ore body occurs in bronzitite on the 65-foot level and in harzburgite on the 130-foot level. Here, too, is evidence that the ore body cuts across the main rock structure.

On the 300-foot level in No. 4 ore body, a small 4-inch "diabase" dike [5] is displaced by the sulphides and replaced

[5] The dike is composed of fine-grained basic material and the term "diabase" used by the writer is merely a field designation and is not to be construed as a final determination.

to some extent by them. Since this dike cuts both the bronzitite and the harzburgite, it indicates that the ore was introduced after the bronzitite and harzburgite had sufficiently "cooled" and crystallized to permit the dike to intrude them and preserve its identity. Near No. 2 ore body occurs a 10-inch diabase dike which shows some sulphide replacement. Here, the dike is a few feet north of the ore body. On the 130-foot level, No. 3 ore body also displaces a 6-inch diabase dike.

The boundaries of the ore bodies in most instances were indistinct; that is, there is a gradual fading out of the mineralization, and the boundary between ore and rock is determinable only by assay, particularly in the case of No. 4 ore body. The

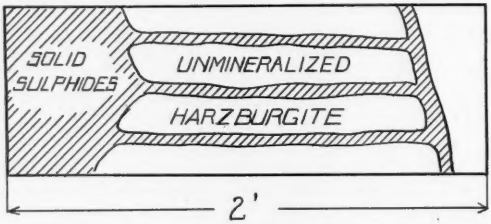

FIG. 4. Longitudinal section showing sulphides making along pseudo-bedding planes in harzburgite.

Rock Shaft and No. 2 ore bodies, however, show, in most cases, well-defined vein-like boundaries between the sulphides and the inclosing rocks, suggesting that the sulphides were introduced along pre-existing fractures. In one case, at the upper level of the Rock Shaft, the sulphides make along the flat joint planes of the harzburgite (these joint planes have been called "pseudo bedding" by Dr. Wagner).

Again, this is more evidence to support the theory that the ore was introduced after the consolidation of the rocks. In every instance, at the time mining was suspended in 1928, the ore bodies were still persistent at the lowest mine workings, and showed no termination as suggested by Dr. Wagner. The deepest ore exposed is No. 4 ore body, which has been proved to a depth of 350 feet.

ORIGIN.

Dr. Wagner[6] points out that the theory of origin must account for:

1. The situation of the deposits, not at the base of the lopolith like the mineralogically very similar Sudbury and Insizwa deposits, but in a fairly well-defined magmatic zone lying almost 4000 feet above the base, and characterized by the extreme heterogeneity of the rocks composing it;
2. The sporadic distribution of the deposits in this zone;
3. The universal presence in the ore of graphite, whereas that mineral is not found away from the sulphide deposits; and the relation between the sulphides and graphite;
4. The unquestionable subsequency of the sulphides to the silicates and that some replacement of silicates by sulphides has taken place.
5. The fact that the majority of the ore bodies, in contradistinction to the magmatic deposits of chromite and magnetite occurring in the lopolith, do not conform to the general pseudo-stratification of the surrounding rocks, but cut across it, the mineralization having to some extent been guided by pre-mineral fractures;
6. The hydrothermal activity following the magmatic stage in the formation of the deposits, as a result of which the primary silicates underwent hydration, and magnesite, pyrite, and siderite were deposited;
7. The abundance in most of the deposits so far opened up of marcasite, a mineral which is not stable at high temperatures.

He then goes on to explain how the theory of magmatic segregation clearly accounts for the deposit; that "graphite" in some way is responsible for the localization of the deposit; that some hydrothermal activity should be expected after the formation of the sulphides; and that the sulphides having cooled last are injected in veins and vein-like bodies; he then concludes by stating:—"the veins and vein-like bodies of solid sulphide ore when fully exposed always exhibit abrupt downward terminations, proving that the ore came from above. This is fully consistent with and indeed strongly supports the assumption that gravity was one of the principal factors involved."

[6] Wagner, Percy A., *op. cit.*, pp. 147, 149, 151.

Schoch,[7] in his discussion of the origin of the deposit, states as follows:

Dr. Wagner, in his Memoir already referred to, contends on page 147 that the disseminated sulphide specks were, in their original form, droplets of non-consolute iron-nickel copper matte, and that the rocks containing them owe their origin to the accumulation, under influence of gravity, of early-formed crystals separating from the parent norite magma, and he goes on to say that "there is thus the strongest presumptive evidence in favor of regarding the ore bodies as local aggregations of such matte droplets."

The process is called the theory of magmatic differentiation, and is a widely accepted theory for the formation of eruptive ore deposits. Dr. Wagner explains at considerable length his reasons for arriving at the foregoing conclusion, and up to that point I am inclined to agree with him. However, he then states in a further paragraph that "the veins and vein-like bodies of solid sulphide ore, when fully exposed, always exhibit abrupt downward termination, proving that the ore came from above." This statement I am unable to reconcile with what I have seen of the solid ore in depth at different points, where as a rule no abrupt termination is visible, and I am disposed to think that the more recent disclosures tend to refute the theory of the ore coming from above and having its origin, therefore, at shallow depth. Moreover, it is difficult to find an explanation for the question why these globules of matte should have concentrated into a number of vertical pipe-like chimneys at widely separated points instead of forming more or less continuous horizontal sheets or lenses of ore, as might reasonably be expected from heavy bodies following the laws of gravity. Judging from the structure of the pipes, the dissemination of the mineral contents, and their relationship to the country rock, it seems more than probable that these deposits have their origin in deep-seated regions.

Their very shape and perpendicular position suggests, to my mind, that the deep-seated concentrated matte, under stress of great pressure and heat, aided by the eruptions of the Pilandsberg, would seek an outlet or outlets and would cause mineral solutions and metallic vapors to rise up through cracks or vents in the norite matrix, and deposit their minerals along these channels, in the process of which a certain amount of replacement of the wall rock was inevitable. In the circumstances, this latter process, which is known as that of pneumatolysis, may therefore be equally responsible for the formation of these deposits.

However, as Dr. Barlow, in his Report on the Origin, Geological Relations and Composition of the Nickel and Copper Deposits of the Sudbury

[7] *Chem. Met. Min. Soc. South Africa*, January, 1929, p. 154.

Mining District, points out, "The origin of these eruptive ore deposits is largely a matter of theory and opinion and after all no really sharp division exists between the two processes, and probably they are both responsible for the resultant product."

The writer has shown in the preceding pages that: (1) The ore bodies are later than both the harzburgite and bronzitite, also the diabase dikes, and (2) what is most important of all, the ore structure is at right angles to the rock structure.

One deposit, the Quartz ore body, occurs 10 feet south from the edge of a quartz outlier that outcrops for a mile north. Large quartzite boulders south of the shaft show that very little erosion of norite can have taken place at this point. Consequently, this ore body could not have "settled out" from overlying norite by gravity.

The writer agrees with Mr. Schoch that Dr. Wagner's theory of "magmatic segregation" is not substantiated by further investigations, but does not agree with Mr. Schoch that the ore bodies might have been formed by pneumatolysis. Inasmuch as such factors as pressure and temperature are relatively unknown, the writer is of the opinion that it is unwise to offer any details of the mechanics of ore formation. He suggests, however, the following: Ore bodies were introduced after the consolidation of the rocks and were formed by agencies which came from "below." Whether the ore bodies were introduced as "solid sulphides" with some attendant hydrothermal action, or formed by replacement from concentrated or weak solutions entirely by hydrothermal agencies, is a problem for the geochemist to decide and is beyond the scope of this paper.

The localization of the deposits is likewise a problem which cannot be accepted as solved on the basis of the "graphite" content of the bronzitite, as postulated by Dr. Wagner.[8] The writer thinks that pre-existing fractures are responsible for the localization of the ore bodies. The presence of the diabase dikes, small though they may be, near and in the ore bodies, indicates that there were some fractures existing before the

[8] "Magmatic Nickel Deposits of the Bushveld Complex," *op. cit.*, pp. 149, 150.

ore bodies were formed, and these pre-existing fractures provided the channels of ore formation. Schoch [9] has well stated the case when, in describing the ore bodies, he says:

> The bulk of the disseminated ore is generally found towards the outer periphery of the pipe, while large masses of pure sulphides will be found nearer the center. The inference to be drawn from this phenomenon is that the concentration of the heavy minerals has been more intensive in the middle of the vent than it has been on the outer periphery, and this arrangement, taken in conjunction with the sausage-like shape of the deposits, raises the question whether the result is consistent with magmatic segregation alone.

The above condition is the logical end when replacement works outward from a central channel-way.

Extended field work [10] over the entire Bushveld Complex has convinced the writer that the nickel deposits are confined to the Pilandsberg area. Schoch has suggested that the Pilandsberg intrusive, by reheating a deep-seated concentrated matte, may have been the cause for the solutions and vapors rising along cracks and vents in the norite, these agencies forming the ore deposits. The deposit at Groenfontein 305, 16 miles north of Vlakfontein 702, is about the same distance from the edge of Pilandsberg intrusive at Vlakfontein. There is probably some genetic connection between the Pilandsberg intrusive and the nickel deposit. More work may clearly reveal this.

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[9] *Chem. Met. Min. Soc. South Africa*, Johannesburg, Transvaal, January, 1929, p. 155.

[10] The writer at this point wishes to express his appreciation to his colleague in the field, Mr. Aubrey Tennant, of Radium, Transvaal, whose knowledge of Dutch and Kaffir, coupled with his technical knowledge of the area, enabled the carrying out of field work with the maximum of results.

A TIN–SILVER VEIN AT SNOWFLAKE MINE, B. C.[1]

H. C. GUNNING.

In the spring of 1929, stannite was identified in the ores of the Snowflake mine by G. S. Eldridge and Company, assayers, Vancouver, B. C. The occurrence has been briefly described by Victor Dolmage [2] and by other engineers.[3] The writer examined the general geology of the district in 1928 and briefly described the mineral deposits.[4] In the fall of 1929 he revisited the property, collected specimens and has recently examined them in the laboratory. In view of the novelty of the occurrence for North America and the additional information available since the appearance of Dolmage's article, it seems that further remarks on the deposit may be of interest.

The Snowflake mine is on Silver Creek, six miles north of the main line of the Canadian Pacific railroad and eighteen miles northeast of Revelstoke. The workings vary in elevation from 5500 to 6000 feet and are near the top and on the southwest slope of a steep ridge of the rugged Selkirk range.

GENERAL GEOLOGY.

The rocks on the property consist of carbonaceous and quartzitic argillites and a few impure calcareous beds that strike northwest and dip from 35° to 65° to the northeast.[5] They are broken by a system of joints that trend northeast and dip steeply southeast, and are locally contorted and sheared. They form part of a thick

[1] Published by permission of the Director, Geological Survey, Canada.

[2] Dolmage, V., *Can. Min. Jour.*, July 5, 1929, pp. 626–627.

[3] B. C. Dept of Mines, Repts. on Snowflake and Waverley-Tangier Mineral Properties, 1928; B. C. Dept. of Mines, Bull. No. 1, 1929. pp. 52–55.

[4] Can. Geol. Surv. Summ. Rept. 1928, Pt. A, pp. 136–193, map 237A.

[5] For information regarding the general geology of the district the reader is referred to Dawson, *Geol. Soc. Amer.*, vol. 2, p. 165, 1891; Daly, R. A., Geol. Surv. Can., Mem. 68, 1915; and to the writer's recent report.

series of argillites, quartzites, mica and chlorite schist, and limestone, which is underlain conformably some three miles southwest of the mine by quartzite, schists, and some interbedded greenstones of obscure origin. Between Silver Creek and Revelstoke these underlying rocks are largely converted to paragneiss and contain many *lit par lit* injections and dikes of orthogneiss, granite, and pegmatite. Numerous stocks of granite, similar to those found in the lower series, cut the upper series of sediments in which the mine lies. One stock outcrops 8 miles south of the mine and another some 7 miles northeast of it. These granitic intrusions, including the dikes and gneisses between Silver Creek and Revelstoke, are correlated, with considerable assurance, with the Mesozoic intrusions that are so abundantly developed in this and other parts of British Columbia. Thus, they are probably of Late Jurassic or Early Cretaceous age and it is believed that their magma or magmas supplied the mineralizing solutions which formed the ore deposits of the district. The sediments that they intrude are pre-Cambrian. They are correlated with the Windermere group of late pre-Cambrian rocks of the adjoining Lardeau map area.[6]

THE SNOWFLAKE VEIN.

On the property a number of quartz veins follow the bedding of carbonaceous argillites, that strike northwest and dip in the neighborhood of 50° to the northeast. At least seven veins have been exposed on the Snowflake and the adjoining Regal Silver ground, but, at the former, one vein has received practically all the development; it has been traced on the surface for several hundred feet and underground by a drift, at a depth of 400 feet, for over 500 feet. This vein is complex and varies in width up to about 17 feet, including the quartz, fragments and partings of wall rock. It pinches and swells along the strike and in places disappears for short distances. The quartz is white and coarsely crystalline and vugs are not uncommon. A rough banding, due to inclusions of argillite, is developed in places. The wall rock is massive and little altered, or is extensively sheared and converted

[6] Can. Geol. Surv. Mem. 161.

to graphitic schist; near or in the vein it may contain abundant pyrite in the form of veinlets and disseminated crystals. Numerous tiny quartz veins follow joints or cracks in the argillites.

Mineralogy.—Pyrite, sphalerite, galena, stannite, chalcopyrite, tetrahedrite, ruby silver, native silver, and scheelite and wolframite have been identified in the ores. Pyrite is commonly coarsely crystalline and occurs in abundance both in the quartz and in the wall rock. Sphalerite is dark brown to black and is less abundant, on the whole, than galena, which is coarse to fine-grained and occasionally gneissic. The stannite is black or very dark steel-gray and is also coarsely crystalline or exceedingly fine grained; in the latter case it is generally intimately mixed with other sulphides. Tetrahedrite, ruby silver, native silver, and chalcopyrite are present as small grains mostly observable only under the microscope. Scheelite, of a light brown color, is rather sparingly distributed as poorly formed crystals or small massive bunches in many parts of the vein, and wolframite has been found as stubby dark brownish-black crystals in one or two places, particularly in a drift fifty feet above the lowest level. No cassiterite has as yet been identified. Although some of the included fragments of argillite are partly replaced by silica, yet replacement does not seem to have been of major importance in the formation of the veins. They seem rather to represent fillings of broad and complex shear zones in the sediments.

Distribution of Ore Minerals.—The metallic minerals are irregularly distributed in shoots, bunches, lenses or disseminations in the quartz vein, large parts of which are barren. They also occur less commonly as small bodies in the crushed argillite immediately adjoining the vein, and the footwall section seems to be slightly more favored in this respect than other parts. To a large extent the sulphides replace the quartz where it has been fractured and crushed. In the old upper workings, a few small bodies of silver-lead-zinc ore were found and in these stannite is sparingly present in most places. A long lower crosscut, driven 900 feet, encountered the vein at a depth of 400 feet, and from this point a shoot of ore, carrying abundant stannite, was de-

veloped for a length of a little over 100 feet to the southeast of the crosscut. A raise from near the southeast end of this ore body was up 290 feet on the dip of the vein at the time the writer visited the property and showed the vein to vary in width from 2½ to 6 feet. The quartz contains irregular bunches of sulphides, the most important mineralization extending from about 25 feet to 70 feet above the adit level. Above this, barren quartz and smaller bunches of ore alternate. The vein on the adit level was drifted on for over 400 feet to the northwest and two or three small bodies of ore were encountered but on the whole this development is disappointing. The main ore shoot in the lower level and for 120 feet up the raise was sampled at 20 foot intervals [7] and returned an average value of: Gold, trace; silver, 6.39 ozs.; lead, 0.65 per cent.; zinc, 5.31 per cent.; copper, 0.94 per cent.; tin, 0.73 per cent., over an average width of 34 inches; but these samples probably included a quantity of low grade vein matter that might be rejected in selective mining. The rich shoot 25 feet up the raise assayed, across 38 inches: Gold, trace; silver, 43.5 ozs.; lead, 7.5 per cent.; zinc, 6 per cent.; copper, 6.5 per cent.; tin, 6 per cent.

The original analysis of the stannite by G. S. Eldridge of Vancouver gave tin, 26 per cent.; copper, 31 per cent.; iron, 3 per cent.; sulphur, 28 per cent; and a strong test for silver was obtained. A small piece of the mineral, as pure as could be obtained, was analyzed by R. J. C. Fabry of the Division of Mineralogy, Canada Geological Survey, and gave the following result:

Tin	26.65
Copper	31.56
Zinc	7.72
Iron (ferrous)	3.65
Manganese	nil
Nickel	nil
Sulphur	29.76
	99.34

Later, similar material was submitted and further tests showed no silver or antimony and a slight trace of lead. This indicates

[7] B. T. O'Grady, B. C. Dept. of Mines, Bull. 1, p. 53, 1929.

that the silver is not contained in the pure stannite; it must belong almost entirely with the galena, ruby silver, and tetrahedrite.

Paragenesis.—Much of the quartz is earlier than the sulphides and is veined and replaced by them, having been quite extensively crushed before they were introduced. There is, however, on the adjoining Regal Silver group, a small amount of watery quartz which is intergrown, in banded structure, with sulphides, and appears to be contemporaneous with them. The scheelite and wolframite probably formed at an early stage in the mineralization but there is little or no evidence on this point in the specimens collected by the writer. The study of hand specimens and polished surfaces indicates that all the sulphides crystallized during a continuous period of mineralization. Pyrite was evidently the first sulphide to crystallize. It is largely veined and replaced by the later sulphides where they occur with it. Sphalerite and stannite are later than pyrite and seem to be about contemporaneous; in some places the stannite appears to be earlier than sphalerite and in others it seems to vein it but the relations are not conclusive. Galena is certainly later than pyrite, stannite, and sphalerite. Chalcopyrite occurs as small specks and tiny veinlets in the sphalerite and occasionally as disseminated particles in the stannite. Ruby silver and tetrahedrite were noted as tiny irregular areas in galena and rarely in stannite. They probably formed during the later stages of mineralization. In the surfaces studied by the writer, ruby silver is more abundant in those from the upper workings than in the ones from the lower level but it does not appear to be supergene. As mentioned above, some of the stannite is very fine-grained and is then intimately admixed with galena, sphalerite, and pyrite. On polished surfaces the stannite is distinctly brown in color, and it slowly tarnishes brown with HNO_3, being negative to all the other reagents used by Davy and Farnham. The brown color cannot be attributed to the presence of included chalcopyrite. Except in the exceedingly fine-grained varieties, it polarizes distinctly and is evidently slightly sheared in places. In some of the coarser varieties distinct twinning is evident with polarized light.

COMPARISONS AND CONCLUSIONS.

So far as is known this is the first occurrence of stannite to be found in Canada. Indeed the mineral has been noted in but a few places in North America. It has been recorded in small amount in the tin-bearing deposits of the Black Hills of South Dakota, and an old analysis from the Peerless mine [8] gave the following results: Sulphur, 28.26; tin, 24.08; copper, 29.81; iron, 7.45; zinc, 8.71; cadmium, 0.33; antimony, trace; insoluble, 1.5. Total, 100.15. Knopf [9] has noted stannite on the west side of Lost River, opposite the mouth of Tin Creek, on Seward Peninsula, where it is associated with topaz, fluorite, wolframite and galena. These ores averaged 22.9 ozs. in silver. Also, it is interesting to note that 0.17 tin was found [10] in zinc concentrates from the Payne mine near Sandon, B. C., and that traces of tin have been found in products of Slocan ores at the Trail smelter, but no tin mineral has as yet been identified in the Slocan deposits.

The Snowflake deposit bears certain resemblances to the tin-silver veins of Bolivia.[11] In many of the Bolivian deposits, as at the Snowflake, stannite, accompanied by pyrite, sphalerite, and other metallic minerals, is found in quartz veins in Paleozoic slates or quartzites intruded by Tertiary quartz porphyries and allied rocks. Similar veins occur also in the intrusive rocks. All the minerals of the Snowflake have been found in the Bolivian deposits. An important difference is that cassiterite, which has not been identified as yet at the Snowflake, is the principal tin mineral in the Bolivian veins, and galena, which is abundantly present at the Snowflake, is absent or but sparingly developed in

[8] Headden, W. P., *Amer. Jour. Sci.* (3), vol. 45, p. 105, 1893.

[9] Knopf, A., "Some Features of Alaskan Tin Deposits," ECON. GEOL., vol. 4, pp. 214–223, 1909.

[10] Mines Branch, Dept. of Interior, Ottawa, Can., 1906. Report of the Commission to Investigate the Zinc Resources of B. C., etc., p. 15.

[11] Miller, B. L., and Singewald, J. T., Jr., "Mineral Deposits of South America," pp. 94–147, New York, 1919. Davy, W. Myron, "Ore Deposition in the Bolivian Tin-Silver Veins," ECON. GEOL., vol. 15, pp. 463–496, 1920. Buerger, M. J., and Maury, J. L., "Tin Ores of Chocaya, Bolivia," ECON. GEOL., vol. 22, pp. 1–13, 1927. Lindgren, W., and Creveling, J. G., "The Ores of Potosi," ECON. GEOL., vol. 23, pp. 233–262, 1928.

many of the South American occurrences. Although it is admitted that further development will probably lead to the discovery of additional minerals at the Snowflake, and possibly cassiterite, it seems that the Snowflake deposit is perhaps more closely related to normal silver-lead-zinc veins than to the cassiterite-bearing veins of Bolivia. In this connection it is interesting to compare the deposit with certain veins of the Zeehan mineral field in Tasmania.[12] In this district early Paleozoic slates, quartzites, and tuffs are intruded by Devonian granite and there is a gradation from cassiterite veins in the granite through copper-lead-zinc contact-metamorphic deposits in which, close to the intrusive, some cassiterite has been found, to normal quartz and siderite veins carrying pyrite, galena, chalcopyrite and occasionally stannite. At the Oonah mine, in the lower temperature belt several miles east of the granite, pyrite, stannite, chalcopyrite and galena, with lesser amounts of bismuthinite, tetrahedrite, wolframite and antimonial lead ores occur in veins with quartz, siderite and occasional fluorite. Siderite is not abundant except in one vein where it is associated principally with chalcopyrite. The stannite persists to a depth of 450 feet, the bottom of the mine in 1910. Just what happened below this is not known to the writer, but the 1923 report of the Secretary of Mines, Tasmania, mentions only the shipment of a few tons by leasers. Although no cassiterite was present in the mine workings, a small lode containing this mineral has been discovered a short distance to the east. In view of the fact that little of the world's tin is obtained from stannite, it is interesting to note that two products, a copper-silver matte and a copper-tin alloy were obtained by metallurgical treatment, the details of which were not available for publication. In " Clark's Lode " at the nearby Zeehan-Queen mine the ore consists of pyrite, stannite, and galena, and quartz is sparingly present.

At the Conrad mine[13] in New South Wales, stannite occurs with galena, zincblende, chalcopyrite and arsenopyrite in a quartz

[12] Twelvetrees, W. H., and Ward, R. K., " The Ore-Bodies of the Zeehan Field," Tasmania Geol. Survey Bull. 8, 1910.

[13] Geol. Survey, New South Wales, " The Mineral Industry of N. S. W.," 1928, pp. 61, 65, 150.

vein in siliceous granite, but in the Tolwong lode, stannite is associated with mispickel, chalcopyrite, and zincblende in slates and quartzites. It seems probable that some of the Tasmanian or New South Wales deposits more closely resemble the Snowflake than the better known Bolivian veins.

There is a small amount of sericite in some of the wall rock at the Snowflake but neither tourmaline, topaz, or fluorite, minerals commonly associated with cassiterite, have been identified. Tourmaline, however, was noted by the writer in association with slight copper mineralization on Albert Creek eight miles south of the mine, and fluorite was identified in an altered lamprophyre dike on Silver Creek.[14]

The question of zoning in hypogene mineral deposits assumes considerable economic importance in the consideration of the Snowflake deposit. Cassiterite is, metallurgically, a much more desirable tin ore than stannite, and if the former mineral were found to take the place of the latter at depth the property would benefit accordingly. This possibility, based on the theory that cassiterite is a higher-temperature mineral than stannite, has been suggested in connection with the Snowflake. An extended but admittedly incomplete search of an extensive and scattered literature on the subject does not offer much factual evidence in support of the hypothesis, however. Any information regarding the subject would be welcomed by the writer. A lateral zoning, in relation to exposed intrusive igneous rocks, has been described in different districts, and occasionally in tin-bearing fields, but evidence of vertical zoning in individual deposits of this type is not so easily found. Lindgren,[15] in speaking of the tin veins of Potosi, Bolivia, says:

"It is equally certain that in the deepest levels the ore is poorer and there are fewer ore shoots than in the upper levels. While there seems to exist a distinct decrease in silver it seems probable that the tin in the ore remains about constant through the whole vertical range of about 750 meters but in the lower levels stannite would seem to be more abundant than cassiterite, while argentiferous tetrahedrite seems to predominate in

[14] Can. Geol. Surv. Summ. Rept. 1928, Pt. A, pp. 148*A*, 149*A*.

[15] ECON. GEOL., vol. 23, p. 242, 1928.

the upper levels. . . . There is no marked indication of vertical or lateral zones of ore minerals."

Far from indicating an increase of cassiterite relative to stannite at depth, this statement seems to indicate that at Potosi the reverse may be true.

As mentioned above, Twelvetrees has shown a distinct zoning, in the Zeehan field of Tasmania, from cassiterite deposits near and in intrusive granite to sulphide veins, some of which contain stannite, from one to five miles from the intrusion. J. T. Singewald, Jr.,[16] on evidence and suggestion from Twelvetree's report, has definitely suggested that a similar vertical zoning might be expected. He does not, of course, intimate that this will occur within the depth that can be reached, at present, by mine workings; nor, as far as the writer knows, has actual development work in the field shed much light on the matter. The ore minerals form irregular shoots in the veins and no vertical zonal arrangement seems to be indicated.

It seems to the writer that, in the present state of our knowledge, it is impossible to tell what relation stannite bears to cassiterite in any definite zonal arrangement of ore minerals; that neither mineral indicates clearly a higher or lower temperature of formation, but that the deposition of one or the other probably depends on the chemical nature of the mineralizing vapors (*i.e.*, sulphur content, presence or absence of volatile constituents, etc.) more than on the factors of temperature and pressure. Consequently, the presence of stannite in a vein indicates that there was tin in the mineralizing solutions but is no assurance that cassiterite will be found at any other place in that vein or indeed in any other veins in the district.

However, whether or not cassiterite is found in the Snowflake deposit, there is a distinct possibility that it may occur in other quartz veins or pegmatite dikes of the district. In a pegmatitic dike near the Silver Creek trail, some four miles from the property, the writer identified, in 1928, a few crystals of beryl, a mineral which is not uncommonly associated with cassiterite in

[16] ECON. GEOL., vol. 7, p. 277, 1912.

pegmatite dikes. Also, cassiterite has been reported, but never authentically proven to occur near the headwaters of Fish Creek, some 15 miles southeast of the Snowflake.

The writer is indebted to Dr. G. A. Young of the Canada Geological Survey, and to Dr. V. Dolmage, for suggestions and discussion.

GEOLOGICAL SURVEY,
OTTAWA, CANADA.

DISCUSSION AND COMMUNICATIONS

WHITE CLAYS IN SOUTHERN SASKATCHEWAN.

Sir:—In a recent issue[1] of this JOURNAL an article on the Origin of the White Clays of Tuscaloosa Age (Upper Cretaceous) in Alabama, Georgia and South Carolina by G. I. Adams, appears to show such a close similarity in many respects to a band of white clays that occur in the southern and southwestern parts of southern Saskatchewan that a brief discussion and comparison is here offered.

These clays, known as the Whitemud series, have their type locality near the town of Eastend, southwestern Saskatchewan, just east of longitude 109°, and occur again in two or three zones eastward as far as longitude 105°.

They have been described by various authors for the Geological Survey and the Dept. of Mines of Canada. The latest report on these clays is by F. H. McLearn,[2] who states that "the exact age of the Whitemud beds is not known. No fossils have yet been found in them. The beds that occupy their stratigraphic position down Frenchman river are of Lance (Eocene?) age, but they are probably of later time. The Whitemud may be early Lance, Edmonton (Upper Cretaceous) or some intervening age."

The massive, kaolinized sandstones of the Whitemud vary up to 70 feet or so in thickness; the refractory clay zone itself is only 10 to 30 feet thick, and a maximum of only about 1000 feet in lateral extent. The mapped outcrop[3] of these clays in the Eastend area strongly suggests deposition by overloaded streams across a coastal plain in a physiographically old age stage.

A bed of carbonaceous shale occurs well within the series. The sediments taking the place of the Whitemud beds, previously men-

[1] No. 6, Sept.–Oct., 1930, pp. 621–626.

[2] McLearn, F. H., Geol. Surv. Canada, Sum. Rept. 1928, Pt. B., pp. 30–45.

[3] Map 212 A, Cypress Hills, Geol. Surv. Canada, Sum. Rept. 1927, Pt. B.

tioned here, were found to contain the fragmentary remains of a large Triceratops-like dinosaur. Conditions at this time apparently do not imply marine deposition.

A proposed theory of origin for these clays has been offered by F. H. McLearn,[4] a part of which is as follows:

> Feldspathic sands were transported to this area (southern Saskatchewan) from some source and after deposition were partly kaolinized in Whitemud time; some of this material, thus altered, still remains undisturbed as the partly kaolinized feldspathic sandstone; some of it, however, was reworked in Whitemud time, sorted, and laid down in shallow depressions, flood-plain shallow lakes, etc., on the old Cretaceous surface, to form the beds of refractory or semi-refractory clay that occur intercalated with beds of partly kaolinized sandstones, silts, etc., in the refractory clay zone. This is a theory of intra-regional kaolinization, or alteration in the area of deposition. No uplift is inferred, only the erosion and redeposition that takes place on any alluvial plain. No considerable thickness is involved. The clay beds are not thick, are irregular, and the entire refractory clay zone is only 10 to 30 feet thick. Special conditions are required, of course, at least a temperate climate, some moisture, a covering of vegetation, and a sufficient periodic fall of the water table to promote weathering.

The author further states that

> the establishment of this hypothesis depends basically on whether it can be shown that the kaolinization of the Whitemud sands took place in Whitemud time. The greater amount of clay and its relatively greater purity in many Whitemud sandstones compared with that in other sands, of the Cretaceous section, suggests that specially favorable conditions may have existed in Whitemud time. More, however, needs to be known of the relative susceptibility to alteration of the sandstones of the local formations.

Whether the Whitemud sediments have come from the east, from the pre-Cambrian area of Manitoba and Ontario, from the west or southwest, i.e. from the Cordillera region, or from sedimentary rocks, is still an open question. There has been much discussion as to the source, based on texture. McLearn[5] concludes his chapter on Whitemud with the statement that:

[4] McLearn, F. H., Geol. Surv. Canada, Sum. Rept. 1927, Pt. B., pp. 35–39.
[5] McLearn, F. H., *op. cit.*, p. 38.

the variation in grain of the Whitemud sandstones and the variation in degree of refractoriness of the Whitemud clays, cited by some authors as evidence of the direction of the source of the Whitemud sediments, are as much stratigraphic or vertical as geographic or lateral variations. The lateral variations need to be restudied in the light of the new correlations of the various Whitemud zones.

Here, as also was concluded of Tuscaloosa clays, a satisfactory explanation must be applicable to all the white clays in the region which are similar in character wherever their source.

In conclusion, it may be said that the above information is presented only for the purpose of calling attention to certain marked similarities between these widely separated white clays.

DOUGLAS F. HAMELIN.

LA FLECHE, SASK.

COAL AS A RECORDER OF INCIPIENT ROCK METAMORPHISM.

Sir: Mr. Campbell's interesting paper on this subject, which appeared in the November issue [1] of ECONOMIC GEOLOGY, brings to mind an occurrence noted by me in Jugoslavia that I would like to place on record as a piece of confirmatory evidence.

In the Pristina District in Southern Serbia, a series of shales, grits, sandstones, and thin dolomites is found and is correlated on lithological evidence with the Flysch formation of Upper Cretaceous age. In this particular area, the beds show no sign of metamorphism but are very gently folded into symmetrical undulations. Ripple marks and sun-cracks are perfectly preserved in the shales, and the sandstones are friable and easily disintegrated by rubbing between the fingers.

The series has been laid down on a floor of serpentine, which is probably of Lower Cretaceous age. During the Dinaradean diastrophism, thrusting from the northeast resulted in masses of serpentine overriding the Flysch beds in the form of nappes.

In the course of mining development, a fine exposure was obtained across one of these thrust contacts, the underground work proceeding from the serpentine into the Flysch beds for a distance

[1] Vol. 25, pp. 675–696.

of 150 meters. The folding of the sedimentary beds is asymmetrical for 10 or 20 meters from the thrust contact but the asymmetry fades into gentle symmetrical folds.

In spite of the force that produced the overthrust, the rocks are still in exactly the same physical condition as they are away from any thrust movement—the sandstone is still friable, the shale still non-indurated.

In seeking for evidence of complete reversal of original structure close to the contact, I was fortunate to find plant remains in a thin layer of calcareous, felspathic sandstone. The remains were composed of stalks and branches of a plant the size of a rose bush; but they were completely carbonized and not determinable; *they had become coal,* exhibiting all the physical properties of that which falls under Mr. Campbell's " Stage E."

Surface exposures of the normal Flysch beds are not abundant and in the case of a solitary outcrop, the metamorphism of the plant remains would have been the geologist's only clue to the forces to which the beds had been subjected.

R. MURRAY-HUGHES.

LONDON, ENGLAND.

COLOR CHARTS AND GEOLOGY.

Sir: About eighteen months ago there appeared the first color chart for use in the description of sedimentary rocks.[1] It represents some six years of effort on the part of contributors, and the result, though frequently criticized, amply justifies the labor. The chart has been described, rather than discussed, in reviews in ECONOMIC GEOLOGY (24, pp. 107–108, 1929) and in the *Journal of Geology* (37, p. 616, 1929). In view of its importance and the serious consideration, pro or con, which has been given it by many, some discussion as to its actual value seems justified.

The colors on the chart are arranged according to Ridgway, an ornithologist; they seem well suited for geologists also, however. Nevertheless, many would disagree with Goldman and

[1] Goldman, M. I., and Merwin, H. E., " Color Chart," National Research Council, Div. of Geol. and Geog., Washington, 1929.

Merwin's methods. Difficulty was encountered in reproducing certain colors accurately; corresponding spaces were left blank on the chart. The effect is to give a series in which steps are here very minute, there relatively enormous. It would be better to make the colors *as nearly as possible* correct and space the steps more widely but uniformly. The wider intervals between colors are not only justified by technical difficulties in reproduction; they are advocated because: (1) very few rocks are colored with sufficient uniformity so that they fall into one of the smaller color-divisions, and (2) considerable experimenting by this reviewer suggests that individuals generally disagree by at least one square in matching rock color with chart color. These latter difficulties are especially noticeable with "gray" rocks. It is evident, therefore, that the chart colors as now arranged frequently present *too* fine a classification.

Incidentally, as pointed out by Prof. W. H. Bucher, it is at least possible that European printers might match color shades more accurately and (since the question of cost has been raised) also at a lower expense, partly because they seem to value prestige in craftsmanship more highly than American houses. The permanency of the colors after exposure is not an important factor if the chart can be replaced at frequent intervals by a new one.

The National Research Council chart comprises two sheets, each measuring 5 x 7-7/8 inches. The sheet size is convenient for most geologic notebooks, but the number of colors called for reduces each individual color to a square of 3/8 inch: this is far too small. Eight pages could well be used, with squares measuring one inch in section. This would afford room for about 24 squares per sheet, or 21 spaces more than used at present, although the pattern of succession would call for adjustments. Anyone who has tried to color-match small chips of rock, as suggested by Goldman and Merwin, has experienced the difficulty of using the smaller squares, especially if the rock has a noteworthy luster.

This reviewer has found it convenient to reduce the subjective difficulty in color comparisons by using a white card into which a square, the size of a single color square, has been cut; this

card is placed over the chart and excludes from view all colors except the one being studied.

In general, geologists seem unnecessarily slow to use the chart. Many say it is impractical without giving it a trial. That it can be employed is shown by the occasional use of its color designations in articles. Glacial geologists, especially in describing the color of unweathered till, would give a far more accurate picture by using this systematic chart than by resorting to equivocal terms such as "dove gray," "buff olive gray," and the like. The designation of the color by Ridgeway's color nomenclature is the chief object to be attained, yet at least two geologists tried to devise for publication a set of popular names *in place* of the technical letters and numbers!

The reviewer wishes to urge upon geologists a serious consideration of this or some other chart. One of the sub-committees of the American Society for Testing Materials—a far more effective agent for color standardization than most organizations of geologists—is displaying interest in color classifications for describing building stones. Perhaps the representation of a color-physicist and an architect on a committee for revising the chart might make its use more feasible and more general. It is timely to define our color terms for rocks before others, not as conversant with the problem perhaps, establish conflicting standards.

CHAS. H. BEHRE, JR.

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REVIEWS

The Mineral Industry of the Far East. By BORIS P. TORGASHEFF. Pp. 512; tables, 322; maps, 14; Bibliography. Chali Company, 6 Kiukiang Road, Shanghai, China. 1930. Price, $10.00.

The Mineral Industry of the Far East is a thorough presentation of the occurrence and production of natural resources in eastern Asia. The author has lived in China and the Far East for many years and writes from the standpoint of a mining economist rather than a geologist. The volume contains over 300 tables dealing with production, trade and reserves, in most cases brought up to 1927. Some 60 mineral products are discussed.

Torgasheff confirms the well-known predictions of Bain with regard to the general poverty in mineral wealth of the Far East, although the general tone of the book is optimistic. China has very large reserves of coal, ranking third in the world in this respect, but none of the other seven regions which are discussed appears to be conspicuous in any resource. Japan leads in mineral production per square mile, but is among the poorest countries in reserves. The annual value of mineral products per square mile in Japan is $2,000, as compared with $1,660 for the United States and $200 for China. On the per capita basis the Russian Far East leads with $16 per year, while Japan is credited with $4 and China with $0.85 per person, in comparison with $50 in the United States. Torgasheff regards the Russian Far East, North Manchuria, Korea, and Indo-China as the most highly mineralized areas and the most attractive localities for development.

Coal is the most valuable product, but the total output of 76,000,000 metric tons is less than 6 per cent. of the world's total. This production is adequate for present needs and may be readily increased as required. The situation with regard to iron and steel is the most pressing metallurgical problem of eastern Asia for the actual output is but one sixth of the present consumption. Furthermore the entire Far East is credited with but 3 per cent. of the known reserves of the world. This fundamental shortage of iron makes it very unlikely that any large scale industrialization can take place in the Orient, although domestic needs may be cared for on a moderate scale.

GEORGE B. CRESSEY.

Handbuch der Experimentalphysik, Teil. 3. Angewandte Geophysik. Pp. xii + 556, figs. 225. Akademische Verlagsgesellschaft M. B. H., Leipzig, 1930. Price, 54 M.

The theory of geophysical methods and their application to geological prospecting are discussed in a thoroughly satisfactory manner in this handbook, which considers all phases of the subject in all their aspects. Beginning with a brief description of the forms and properties of the components of the earth's crust and their variations under changing conditions, by H. Reich, the book proceeds to its main purpose—a discussion of the application of geophysical methods to the discovery of buried masses and crustal structures.

It treats its matter under five heads: (1) Gravimetric methods of applied geophysics, by K. Jung, (2) Seismic methods, under two subheads, Airquakes, by O. Meisser and Earthquakes, by H. Martin, (3) Magnetic methods, by H. Haalck, (4) Electric methods, by J. N. Hummel (the theory) and W. Heine (the application), and (5) Radioactive methods, by J. N. Hummel.

Under each division of the subject the theoretical principles upon which the methods are based, and the instruments through which they are applied are described in detail, the meaning of the measurements obtained is explained and the results are interpreted. Many illustrations are given which show how the methods may be employed to discover unseen features beneath the surface.

The book is richly illustrated with diagrams and contains about a thousand literature references. It is an excellent compendium of knowledge of the modern physical methods of exploration. It is well printed and substantially bound.

W. S. Bayley.

Elementary Economic Geology. By H. Ries. Pp. 360, pls. 29, figs. 136. John Wiley & Sons, New York, 1930 (Dec.). Price, $3.75.

This book is a condensation of the older and well known "Economic Geology" by the same author, but is 500 pages shorter. It is presented for use in a one-term course in economic geology. In its preparation, the same arrangement and grouping has been followed as in the larger work but different emphasis has been placed on the subject matter. For example, the descriptions of individual localities and occurrences have been greatly reduced; the discussion of principles, less so. New footnote references are introduced but the lengthy bibliographies at the end of each chapter have been omitted.

The arrangement is: Part I, Non-metallics, considered under twelve chapter headings; Part II, Ore Deposits, considered under eight chapter

headings, according to metals or groups of metals. Each non-metallic is dealt with according to physical properties, occurrence, distribution, uses, mining and preparation, and production. For each metal there is a brief description of the minerals, occurrences, and types of deposits according to genesis. Important deposits are sketchily described.

The part dealing with each substance is of necessity brief, and the effect on the reader is a kaleidoscopic view of the whole gamut of mineral deposits unknit together. However, each individual picture is well proportioned for such a book, and reliable. One wonders, however, why the Utah Copper Company Mine at Bingham, Utah, is included under "Contact-Metamorphic Deposits;" and under "disseminated ores" "formed by circulating waters" mention is made of the great low-grade copper deposits of Ray, Miami, Ajo, and Ely, whereas Utah Copper, the daddy of them all, is not included.

The book, however, is one that should prove of value to those who desire a dependable text for an abbreviated course in economic geology. The publishing is of the usual high Wiley standard.

ALAN BATEMAN.

Bruch und Fliess-Formen der Technischen Mechanik und ihre Anwendung auf Geologie und Bergbau: Band II, Scher Form, Band III, Zerreiss Form. (Break and Flow Forms of Technical Mechanics and their Application in Geology and Mining; II Shear Forms, III Tear Forms.) By ERICH SEIDL. Berlin, 1930.

Seidl starts with a description and discussion of the shear and tear forms that are obtained in the engineering test laboratory and then shows how similar forms may be recognized in geologic structures. A central and suggestive thought of Chap. III is that at the point of incipient breakage in a block under tension, the constriction bends the upper portion of the block down and the lower portion of the block up. Seidl develops this thought and shows that under varying conditions horizontal tension may produce a structure that may be a graben near the surface and a horst at great depth, or may be mainly a horst or mainly a graben. He uses this thought to explain the formation of German salt domes, the structure of the Bavarian Alpine foreland, and the great Rift Valley. These chapters are profusely illustrated with photographs of the results of actual tests in the laboratory, chiefly on metal test plates, with diagrammatic sketches, with photographs of geologic structures in the field, and with geologic maps and sections. The study presented is interesting and suggestive. The illustrations alone may be of considerable interest to a geologist who does not read German well.

The present two chapters are part of a more extensive work, the other chapters of which will appear shortly.

DONALD C. BARTON.

Living Africa. By BAILEY WILLIS. Pp. 320, pls. 22, maps 8. Whittlesey House, McGraw Hill Book Co., New York, 1930. Price, $4.00.

This is a story in popular form of a well known geologist's wanderings through the Rift Valley section of Central Africa, where he went to study rift valleys and the Rift Valley volcanoes. It is written in light vein and simple language and tells of the features of this great region—a tale of its huge rifts, its peculiar rivers, great lakes, and active volcanoes. Game, camp life, and humorous and philosophical remarks about the people and the country hold the reader's interest. It is not strictly geology but a story told by a geologist for the general reader. Nevertheless the geologist may obtain much interesting information from it, and it is delightful reading for anyone interested in travel or in this part of Africa.

ALAN BATEMAN.

Sons of the Earth. By KIRTLEY F. MATHER. Pp. 272, pls. 8, figs. 83. Norton & Co., New York, 1930. Price, $3.50.

The substance of this book was presented in eight lectures under the title of "The Geologic History of Mankind," at the Lowell Institute in Boston last spring. The chapter headings give an idea of the content: Mother Earth's Diary; The Stream of Life; The Family Tree of the Higher Vertebrates; Man's Ancestral Lineage; Artists and Artisans of the Great Ice Age; The First Families of America; The Heritage from Mother Earth; The Outlook for the Future. The first chapter presents a concept of geology and of geologic time. The remaining chapters deal with popularized organic evolution and early man.

The book is fascinatingly written for popular reading and the author is to be congratulated for making the subject so entertaining. Even geologists would enjoy it.

A History of Science. By W. C. D. DAMPIER-WHETHAM. Pp. 514, figs. 14. Macmillan Company, New York, 1929. Price, $6.00.

This book in ten readable chapters traces the history of science from the ancient world to the latest theories in physics, biology, and astronomy. The chapter headings show its content: Science in the Ancient World; The Middle Ages; The Renaissance; The Newtonian Epoch; Nineteenth Century Physics; Biology, and Science and Philosophic Thought; Recent Developments in Biology and Anthropology; The New Era in Physics; Scientific Philosophy and Its Outlook.

The book is a scholarly piece of work and is of intense interest to the scientist and layman alike. It should be read by all students of science.

BOOKS RECEIVED.

A Geologic Study of the Madden Dam Project, Alhajuela, Canal Zone. By F. REEVES AND C. P. ROSS. Pp. 49, pls. 13, figs. 5. U. S. Geol. Survey Bull. 821–B, 1930. Price, 40 cts. General geology, water table, reservoir leakage, foundations, construction materials, recommendations.

Surface Water Supply of the United States: 1926, *Part II,* South Atlantic Slope and Eastern Gulf of Mexico Basins. Pp. 118. W. S. Paper 622. Price, 20 cts. **1927,** *Part IV,* St. Lawrence River Basin. Pp. 156. W. S. Paper 644. Price, 25 cts. *Part IX,* Colorado River Basin. Pp. 99. W. S. Paper 649. Price, 20 cts. *Part X,* The Great Basin. Pp. 97. W. S. Paper 650. Price, 20 cts. U. S. Geol. Survey, 1930.

Chemistry of Leaching Covellite. By J. D. SULLIVAN. Pp. 18, figs. 7. U. S. Bur. Mines, Tech. Paper 487, 1930. Price, 5 cts.

List of Publications, U. S. Bureau of Mines, 1910–1930, with index by subjects and authors. Washington, 1930.

Potash Bibliography to 1928 (annotated). U. S. Bur. of Mines Bull. 327. Pp. 578. Washington, 1930. Price, 90 cts.

Greensand Bibliography to 1930 (annotated), with a chapter on Zeblite Water Softeners. By R. N. SHREVE. Pp. 78. U. S. Bur. Mines Bull. 328, 1930. Price, 15 cts.

Permissible Methane Detectors. By A. B. HOOKER, W. J. FENE, and R. D. CURRIE. Pp. 30, figs. 16. U. S. Bur. Mines Bull. 331, 1930. Price, 10 cts.

Refining of Light Petroleum Distillates. By H. P. RUE and R. H. ESPACH. Pp. 111, figs. 42. U. S. Bur. Mines Bull. 333, 1930. Price, 25 cts.

Insoluble Residues as a Guide in Stratigraphic Studies. By H. S. MCQUEEN. Pp. 32, pls. 12. Missouri Bur. Geol. and Min., Appendix I, 56th Ann. Rept. Rolla, Mo., 1931. An excellent means of correlation of non-fossiliferous drill samples.

Asbestos in the Union of South Africa. By A. L. HALL. Pp. 324, pls. 37, figs. 44. Union of So. Africa Geol. Surv. Mem. 12, Pretoria, 1930. Price, 7 s, 6 d. Monographic study of properties, occurrence, distribution, geology, and technology, of chrysotile, crocodilite, amosite, tremolite, and anthophyllite asbestos minerals.

Annual Report of the Geological Survey Department, Uganda Protectorate, for 1929. Pp. 43. Entebbe, Uganda, 1930. Some accounts of volcanic and rift valley regions.

Mineral Production of India, 1924 to 1928. Records, Geol. Survey of India, Vol. LXIV, 1930. Pp. 446, tables 142, pls. 6, index pp. xcvi. Occurrence, history, mining, production, treatment, exports, of the various mineral products.

Entstehung, Veredlung und Verwertung der Kohle. By K. A. REDLICH, J. C. BREINL, H. TROPSCH, et al. Pp. 359, figs. 86, tables 5. Gebrüder Borntraeger, Berlin, 1930. Price, 33 M. A valuable group of papers. Considerable technology.

The Salt Industry of Canada. By L. H. COLE. Pp. 116, pls. 15, figs. 31, maps 2, tables 13. Canada Mines Branch No. 716, Ottawa, 1930. Price, 20 cts. Geologic occurrence; mineralogy; distribution; and industry.

Geology of Southern Alberta and Southwestern Saskatchewan. By M. Y. WILLIAMS and W. S. DYER. Pp. 160, pls. 5, figs. 4, bibliog. Canada Geol. Survey Mem. 163, Ottawa, 1930. General geology, natural gas, petroleum, coal, building materials.

Canada Geological Survey, Summary Report, 1928, Part C, No. 2218, Ottawa, 1931. Pp. 115. Michipicoten area, Ont., by L. J. Weeks; Southwestern Part of Sudbury Nickel Irruptive, by W. H. Collins; Mineral Deposits, Rush River, Woman River district, Ont., by H. M. Bannerman; Desmeloizes Area, Abitibi District, Que., by J. B. Mawdsley; Upper Devonian and Bonaventura Conglomerate, Escuminac Bay, Que., by E. M. Kindle; Mineral Occurrences, New Brunswick, by F. J. Alcock; Deep Borings in Eastern Canada, by D. C. Maddox.

The Mineral Industry of New Jersey for 1928. Compiled by M. E. JOHNSON. Pp. 29, pls. 3. Dept. Cons. and Dev. of New Jersey, Bull. 34, 1930.

Laboratory Concentration of the Missouri Iron Ores of Iron Mountain and Pilot Knob. By F. D. DEVANEY and S. R. B. COOKE. Pp. 38, figs. 17. Bull. Sch. Mines and Met., Univ. of Missouri, Tech. Ser. II, No. 3. Rolla, Mo., 1930. (In coöperation with the Miss. Valley Exper. Sta., U. S. Bur. Mines.) General geology, petrology, and concentration tests. The fine-grained character precludes gravity concentration; roasting and magnetic separation prove satisfactory.

National Survey of Fuel Oil Distribution, 1929. By E. B. SWANSON. Pp. 30. U. S. Bur. Mines Rept. Amer. Petr. Institute, 1930.

Research Needs of Illinois' Coal Industry: A Symposium. Pp. 89, figs. 32. State Geol. Surv. Coöperative Min. Ser. Bull. 33, Urbana, 1930. Recovery, preparation, marketing, utilization, research.

Reports of the Norwegian Svalbard Expeditions. Ed. by ADOLF HOEL. *No. 29.* Franz Joseph Land: Natural History, Discovery, Exploration and Hunting. By Gunnar Horn. Pp. 54, figs. 4, map (In English).

Price, Kr. 5.00. *No. 30.* Beiträge zur kenntnis des Oberdevons Ost-Grönlands, by A. K. Orvin; Oberdevonische Fischreste aus Ost-Grönlands. By A. Heintz. Pp. 46, figs. 4, pls. 4 (In German). Price, Kr. 4.00. Jacob Dybwad, Oslo, 1930.

Analyses of the Coals of Ohio. By J. A. BOWNOCKER AND E. S. DEAN. Ohio Coal Supply and Its Exhaustion. By F. A. Ray. Pp. 360, maps 6. Ohio Geol. Survey, 4th Ser., Bull. 34. Columbus, 1929.

Stabilization of the Petroleum Industry. By L. M. LOGAN, JR. Pp. 248, index. Univ. of Okla. Press, Norman, Okla., 1930. Price, $2.50. The industry; nature and origin of crude oil; production; marketing; methods of stabilization. A worth-while book to conservationists and petroleum men.

New Geological Investigations, Dutch East Indies. Beknopt Versalg over de Uitkomsten van Nieuwe Geologische Onderzoekingen in de Padangsche Bovenlanden. By K. A. F. R. MUSPER. Pp. 67, figs. 16, map. Jaarb. Mijnw. in Nederlandsch-Indië, 1929, Weltevreden, 1930. Interesting structural geology.

Economic Relations of Silver to Other Metals in Argentiferous Ores. By C. W. MERRILL. Pp. 29. U. S. Bureau of Mines, Econ. Paper 10, 1930. Statistical analyses of silver production from ores and countries.

Annual Report of the Director, U. S. Bureau of Mines, for year ending June 30, 1930. Pp. 54, figs. 2. U. S. Bur. Mines, 1930.

Geology and Petrology of the Wichita Mountains. By M. G. HOFFMAN. Pp. 82, pls. 22, figs. 4, map. Oklahoma Geol. Surv. Bull. 52, Norman, 1930. Physiography; stratigraphy; historical; petrology of the gabbros, anorthosites, granophyres, and dike rocks.

Micropaleontology of the Wetumka, Wewoka, and Holdenville Formations. By A. S. WARTHIN, JR. Pp. 94, pls. 7. Oklahoma Geol. Surv. Bull. 53, Norman, 1930.

A Geomagnetic Survey of the Bauxite Region in Central Arkansas. By N. H. STEARN. Pp. 16, pls. 4, figs. 4. Arkansas Geol. Surv. Bull. 5, Little Rock, 1930. Arkansas bauxite is associated with syenite; hidden syenite areas were determined.

St. Peter and Older Ordovician Sandstones of Northern Arkansas. By A. W. GILES. Pp. 187, pls. 13, figs. 22, tables 57. Arkansas Geol. Surv. Bull. 4. Little Rock, 1930. The geology, lithology, petrography and physical and chemical features of the sandstone; its use for glass and metallurgical and chemical purposes.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

SCIENTIFIC NOTES AND NEWS

E. S. Bastin, of the University of Chicago, has been elected president of Section E, American Association for the Advancement of Science.

David White, of the U. S. Geological Survey, recently completed a series of six lectures delivered at Yale University on the subject of the Geology of Coal. The lectures were followed by round table discussions.

K. C. Heald, staff geologist, Gulf Companies, Pittsburgh, Pa., has been elected a fellow of the Royal Geographic Society, London.

W. E. Wrather, of Dallas, Texas, gave a course of lectures on petroleum geology at Northwestern University, March 2–13.

Waldemar Lindgren, of the Massachusetts Institute of Technology, is taking several months' vacation in Europe.

J. T. Singewald, Jr., professor of economic geology at Johns Hopkins University, has been appointed treasurer of the Economic Geology Publishing Company.

Kirk Bryan, of the department of geology, Harvard University, will give a series of lectures at Northwestern University, March 16–20, on the Geology of Engineering Problems. Sherwin F. Kelly, consulting geologist and geophysicist of New York City, will lecture there on March 24–27 on Geophysical Methods.

W. E. Cockfield, superintendent of the British Columbia division, Geological Survey of Canada, has been elected chairman of the mining bureau of the Vancouver Board of Trade.

H. G. Ferguson, in his capacity as chairman of the Excursion Committee of the International Geologic Congress, 1932, has been making a tour of the United States, going over the various excursion routes and making plans for the details of the excursions and guide books.

C. K. Leith, of the department of geology, University of Wisconsin, lectured before the Western Society of Engineers at Chicago on January 26, on "Mineral Resources and Some of Their Newer Political and International Relations."

Hugo Böckh has been made Director of the Hungarian Royal Geological Survey, ranking as Under-Secretary of State.

Ira Joralemon, of San Francisco, was a recent visitor in New York City and Boston, Mass.

Victor Dolmage was recently re-elected president of the British Columbia Chamber of Mines.

Gardner Edwards, after five years as assistant superintendent of the Ahmeek Mine, Calumet & Hecla Consol., has taken the position of mine superintendent for Bwana M'Kubwa, at N'Kana, Northern Rhodesia.

Bela Low, mining engineer, and Sherwin F. Kelly, geologist and geophysicist, have established an office in New York City for consulting service in co-ordinated mining, geology, and geophysics.

J. Volney Lewis, 21 State Street, New York, has joined the staff of A Century of Progress, with headquarters at Administration Building, Burnham Park, Chicago. He is to organize the work in Geology, Mining, and Metallurgy for the Chicago International Exposition in 1933, with the coöperation of the National Research Council. The keynote of this Exposition will be the progress of the century 1833–1933 in science, with emphasis on the service of science to civilization.

Oliver B. Hopkins, chief geologist, Imperial Oil Company, Toronto, Canada, is making a trip to Colombia and Peru to inspect properties of the International Petroleum Company.

Walter J. Yeaton has resigned his position as associate professor of geology in the University of West Virginia, to engage in consulting work in Southern California.

N. L. Bowen, of the Geophysical Laboratory, Washington, D. C., has been awarded the Bigsby medal of the Geological Society of London, for the excellence of his work on the physical chemistry of igneous rocks.

Carl Beal, A. H. Heller, and Grant Corby, petroleum geologists of Los Angeles, Calif., have dissolved partnership and reorganized under the name of Beal and Corby.

R. N. Nelson, of the Standard Oil Company, Los Angeles, Calif., has gone to Java to engage in geological work there.

Walter F. Pond, state geologist of Tennessee, is president of the Engineering Association of Nashville for the year 1931.

Harrison Schmitt announces the opening of an office for consulting mining geological work at 513 Mills Building, El Paso, Texas.

J. C. Vivian, of the Institution of Mining and Metallurgy, London, has gone to Central America.

William Bowie, head of the U. S. Coast and Geodetic Survey, delivered his presidential address before the Washington Academy of Sciences on January 15, on "Shaping the Earth."

The thirty-second annual meeting of the Canadian Institute of Mining and Metallurgy was held at Chateau Laurier, Ottawa, March 4–6.

The Deutsche Geologische Gesellschaft announces among other events on its 1931 program an excursion to Goslar, May 14–16, and one to Lapland, July 19–31, also on April 1 a discussion of Haarmann's new theory of Mountain Building (Oszillationstheorie).

The American Association of Petroleum Geologists will hold its 16th annual convention in San Antonio, Texas, March 19–21. An interesting technical program is set forth, with excellent papers on South Texas, and separate sessions for geophysicists and paleontologists. An unusual list of entertainments has been arranged. In addition, five field trips are planned, namely: (1) Darst Creek-Luling, March 18; (2) Laredo-Corpus Christi, March 21; (2-A) Mexico, March 21; (3) Edwards Plateau, March 22; (4) Marathon Area, March 21.

The Tulsa Geological Society has elected officers for 1931 as follows: president, R. S. Knappen, Gypsy Oil Company; first vice-president, F. A. Bush, Sinclair Oil and Gas Company; second vice-president, C. L. Severy, 816 Kennedy Building; secretary-treasurer, R. J. Cullen, Twin State Oil Company; council, H. F. Wright, L. E. Kennedy, H. E. Rothrock.

The Mineralogical Society of America announces that it is compiling a list of the more important mineral collections, public and private, in the United States and Canada, to be published later as a Directory. Information is desired particularly of the smaller private collections, many of which were gathered from localities no longer available. Valuable scientific and economic contacts can thus be established between owners and collectors. Accordingly, those who own general or specialized collections are asked to coöperate by sending their names and addresses, brief notes about the collections, and information of other collections or small local dealers, to S. G. Gordon, Philadelphia Academy of Natural Sciences, Logan Square, Philadelphia.

S. J. Cook, general secretary of the Fifth Pacific Science Congress, announces that preliminary arrangements are being made for the meeting to be held in Victoria and Vancouver, British Columbia, during May and June, 1932. This is the first of these meetings to be held on the American side of the Pacific. Frank D. Adams, McGill University, Dean W. R. Brock of the University of British Columbia, and S. J. Schofield of the same institution, are on the executive committee of the Congress.

H. M. Ami, a distinguished geologist of the Geological Survey of Canada, died at Mentone, France, on January 4.

The recently published 20-volume index (336 pages) of ECONOMIC GEOLOGY for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.